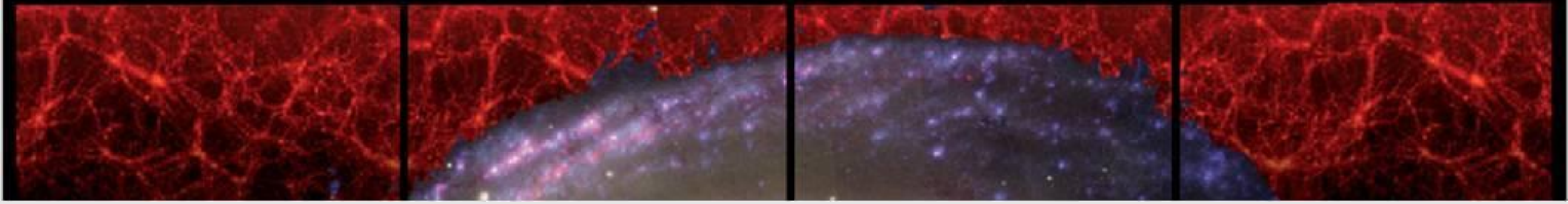


TESTING THE NATURE OF DARK MATTER IN GALAXIES

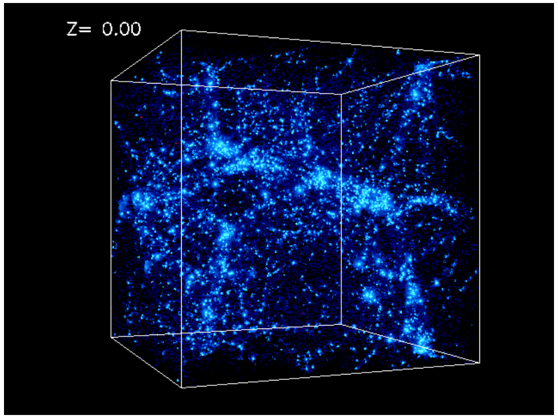
Paolo Salucci

SISSA

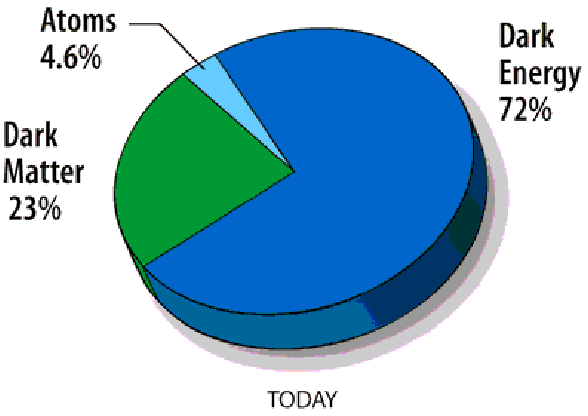
Chalonge school, 25/ 7 / 2013

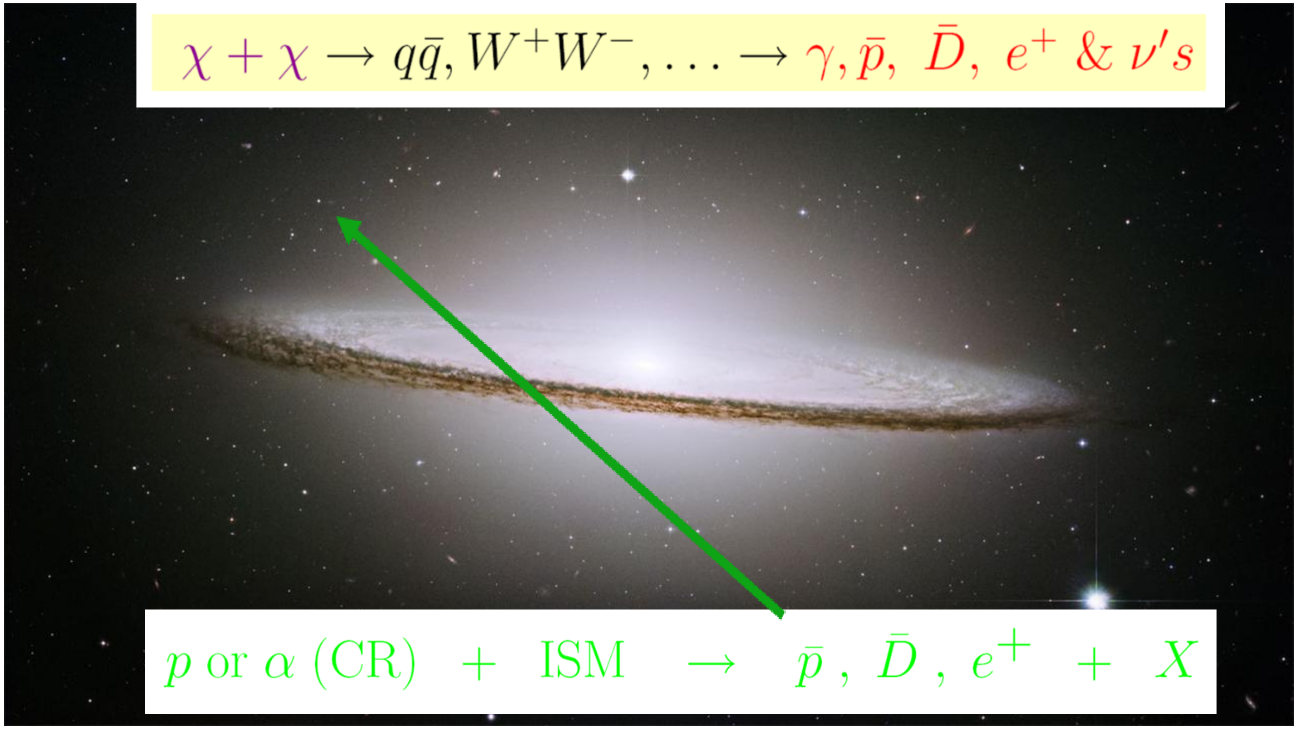
Outline

Dark Matter is the main protagonist in the Universe



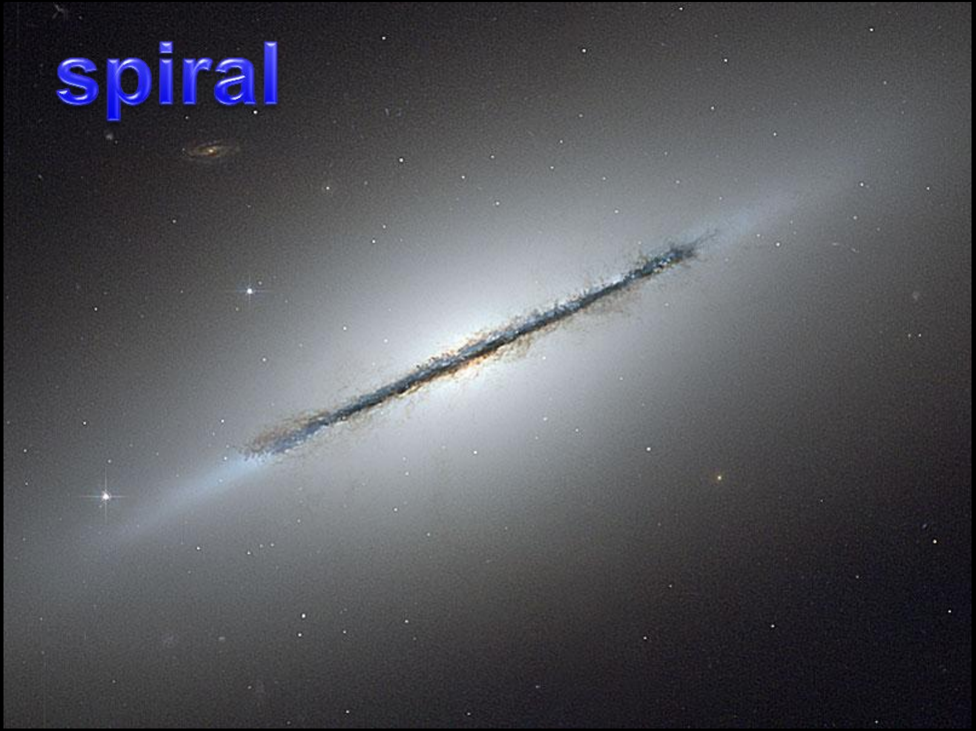
Dark Matter in Galaxies





$$\chi + \chi \to q\bar{q}, W^+W^-, \ldots \to \gamma, \bar{p},\ \bar{D},\ e^+\ \&\ \nu's$$

$$p \text{ or } \alpha\ \text{(CR)}\ +\ \text{ISM}\ \to\ \bar{p}\,,\ \bar{D}\,,\ e^+\ +\ X$$

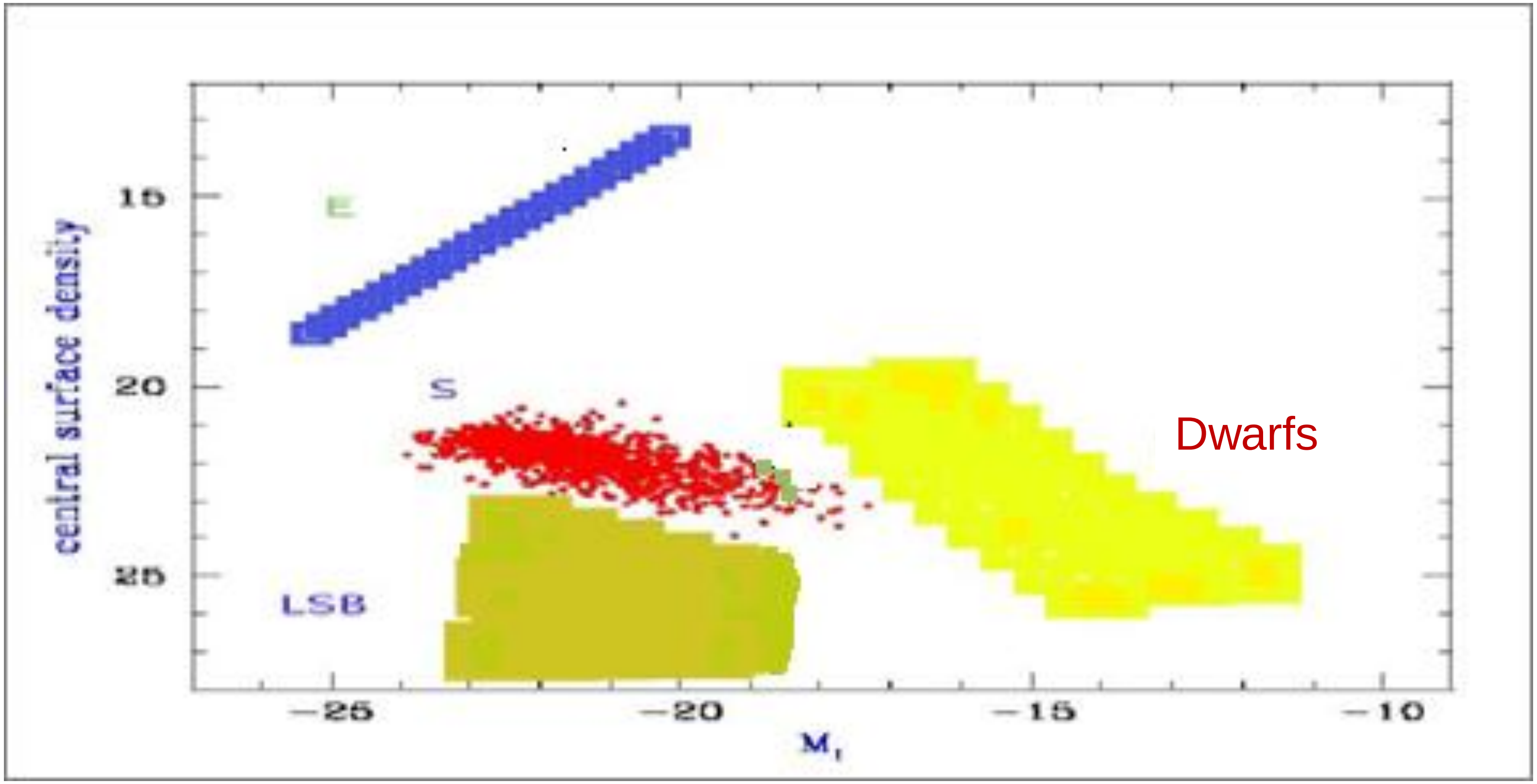


OLD
PHENOMENON
NEW
PARADIGM

The Realm of Galaxies

The range of galaxies in magnitudes, types and central surface densities : 15 mag, 4 types, 16 mag arsec^{-2}

Central surface brightness vs galaxy magnitude



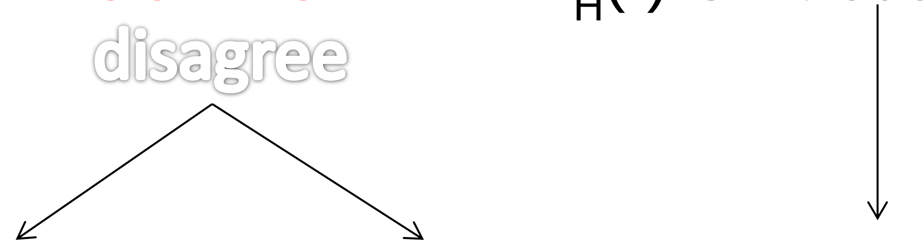
denser

more luminous

What is Dark Matter ?

The radial profile of the gravitating matter M(r) does not match that of the luminous component $M_L(r)$.

A **MASSIVE DARK COMPONENT** $M_H(r)$ is introduced :



$$\frac{d\log M(r)}{d\log r} = \frac{M_L(r)}{M(r)}\frac{d\log M_L(r)}{d\log r} + \frac{M_H(r)}{M(r)}\frac{d\log M_H(r)}{d\log r}$$

M(r), $M_L(r)$, dlog $M_L(r)$/dlog r **observed**

The DM phenomenon can be investigated only if we **accurately** meausure the distribution of: Luminous matter $M_L(r)$ and Gravitating matter M(r)

N-BODY LCDM SIMULATIONS

a conspiracy theory

ΛCDM Dark Matter Density Profiles

The density of virialized DM halos of any mass described at all times by an Universal profile (Navarro+96, 97).

$$\rho_{NFW}(r) = \delta\rho_c \frac{r_s}{r} \frac{1}{(1+r/r_s)^2}$$

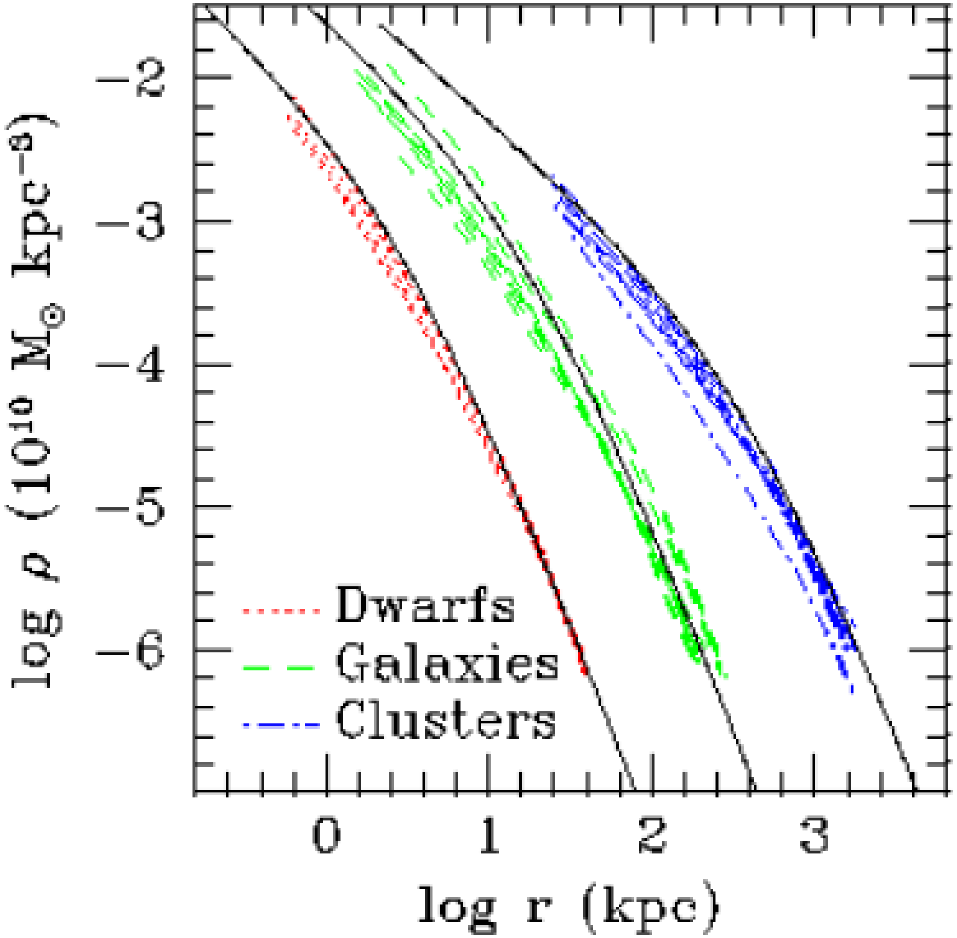
$$c = \frac{R_{vir}}{r_s}$$

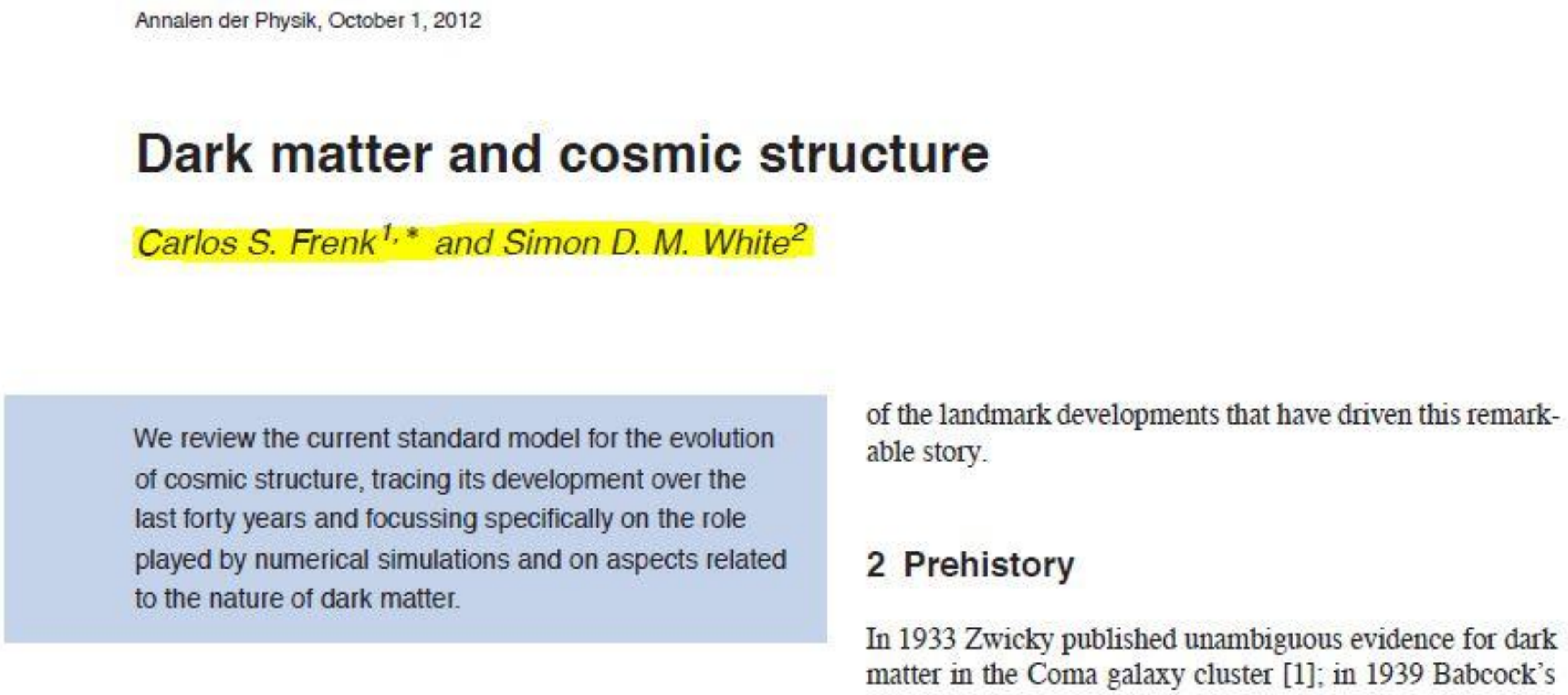
concentration

halo size $R_{vir} = 260 \left(\frac{M_{vir}}{10^{12}\ M_\odot}\right)^{1/3}\ kpc$

$$c(M_{vir}) = 9.35 \left(\frac{M_{vir}}{10^{12}\ M_\odot}\right)^{-0.09}$$

Klypin, 2010





Annalen der Physik, October 1, 2012

Dark matter and cosmic structure

Carlos S. Frenk[1,*] *and Simon D. M. White*[2]

We review the current standard model for the evolution of cosmic structure, tracing its development over the last forty years and focussing specifically on the role played by numerical simulations and on aspects related to the nature of dark matter.

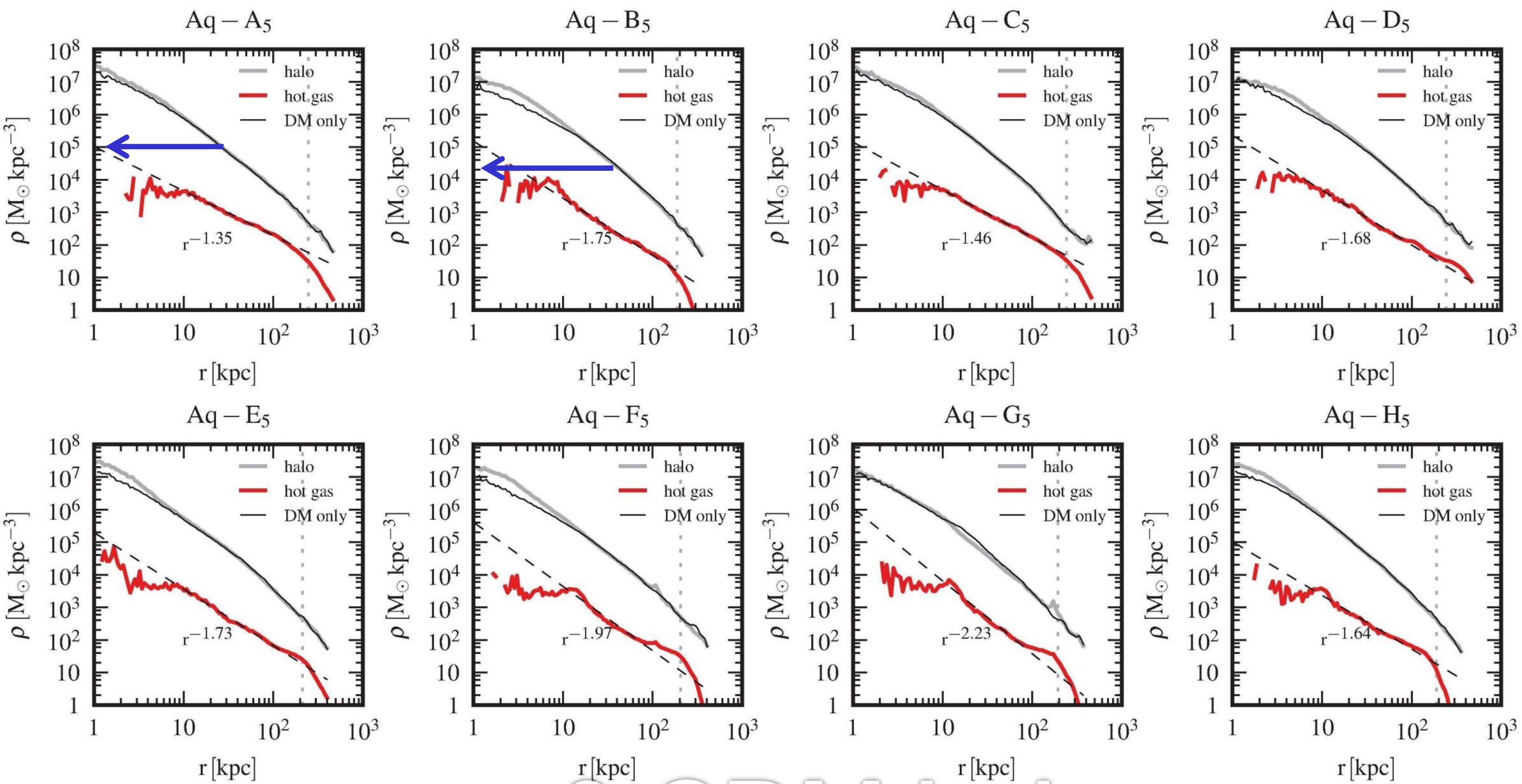
of the landmark developments that have driven this remarkable story.

2 Prehistory

In 1933 Zwicky published unambiguous evidence for dark matter in the Coma galaxy cluster [1]; in 1939 Babcock's

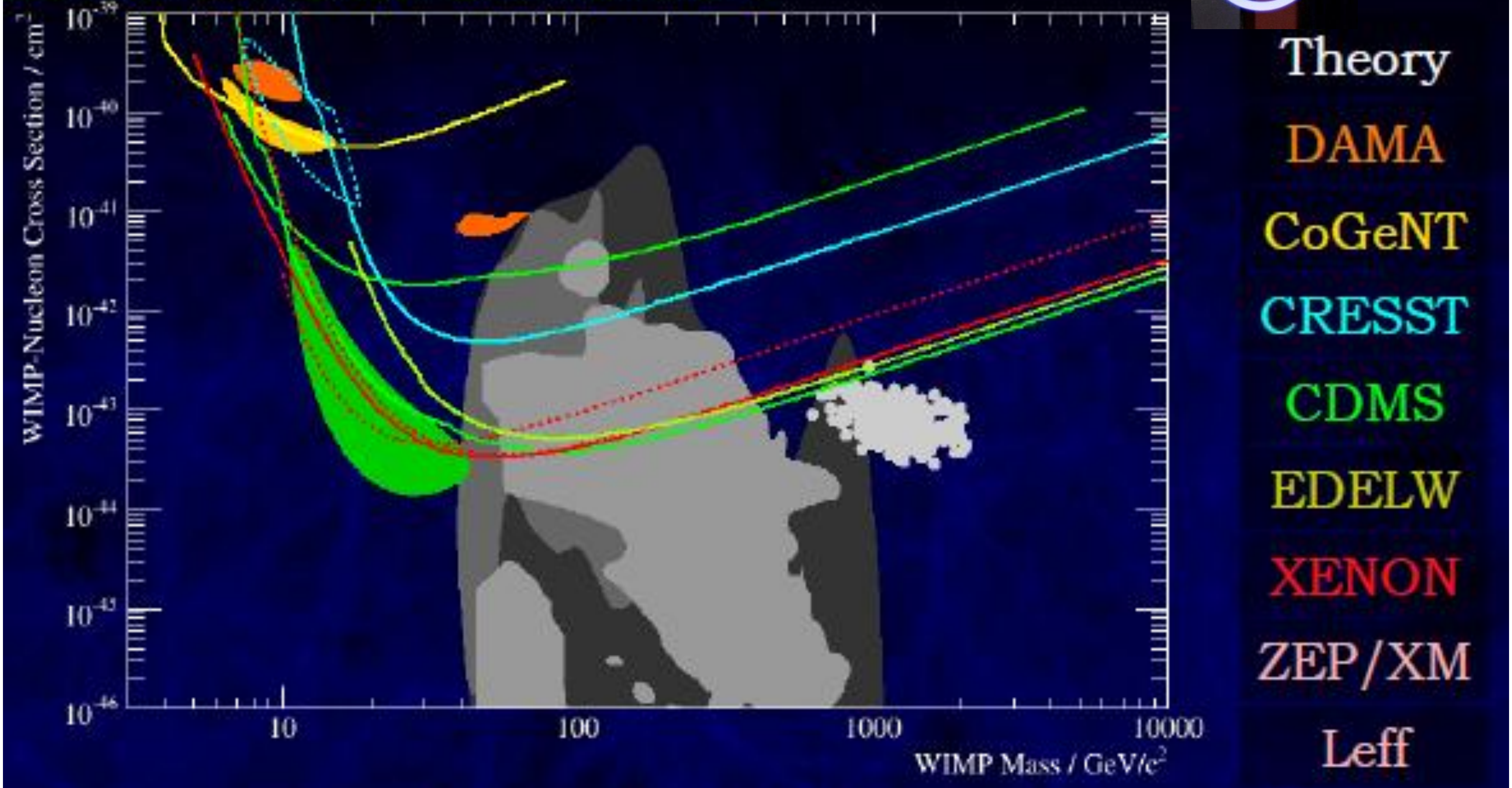
Can Dirty Physics, GastroPhysics, Complex Physics change it all? We observe baryons… Marinacci et al +13

Disc galaxies in moving-mesh cosmological simulations 21



z = 0 CDM halos

Summary



A very active and versatile field of research
many hints to follow up, many promising experiments

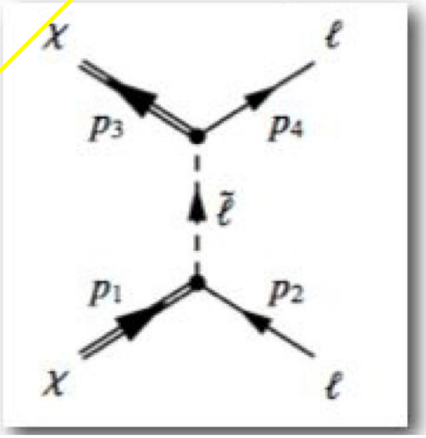
Gamma ray flux on detector on Earth from DM annihilation in DM halos

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi)=\underbrace{\frac{\langle\sigma v\rangle_{ann}}{4\pi m_\chi^2}\Sigma_f B_f \frac{dN_\gamma^f}{dE_\gamma}}_{\text{Particle Physics}}\times\underbrace{\frac{1}{2}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{l.o.s.} dl(\psi)\rho_\chi^2(r)}_{\text{Astrophysics}}$$

Particle Physics

Astrophysics

ATOMIC PHYSICS




Nelson et al. 93

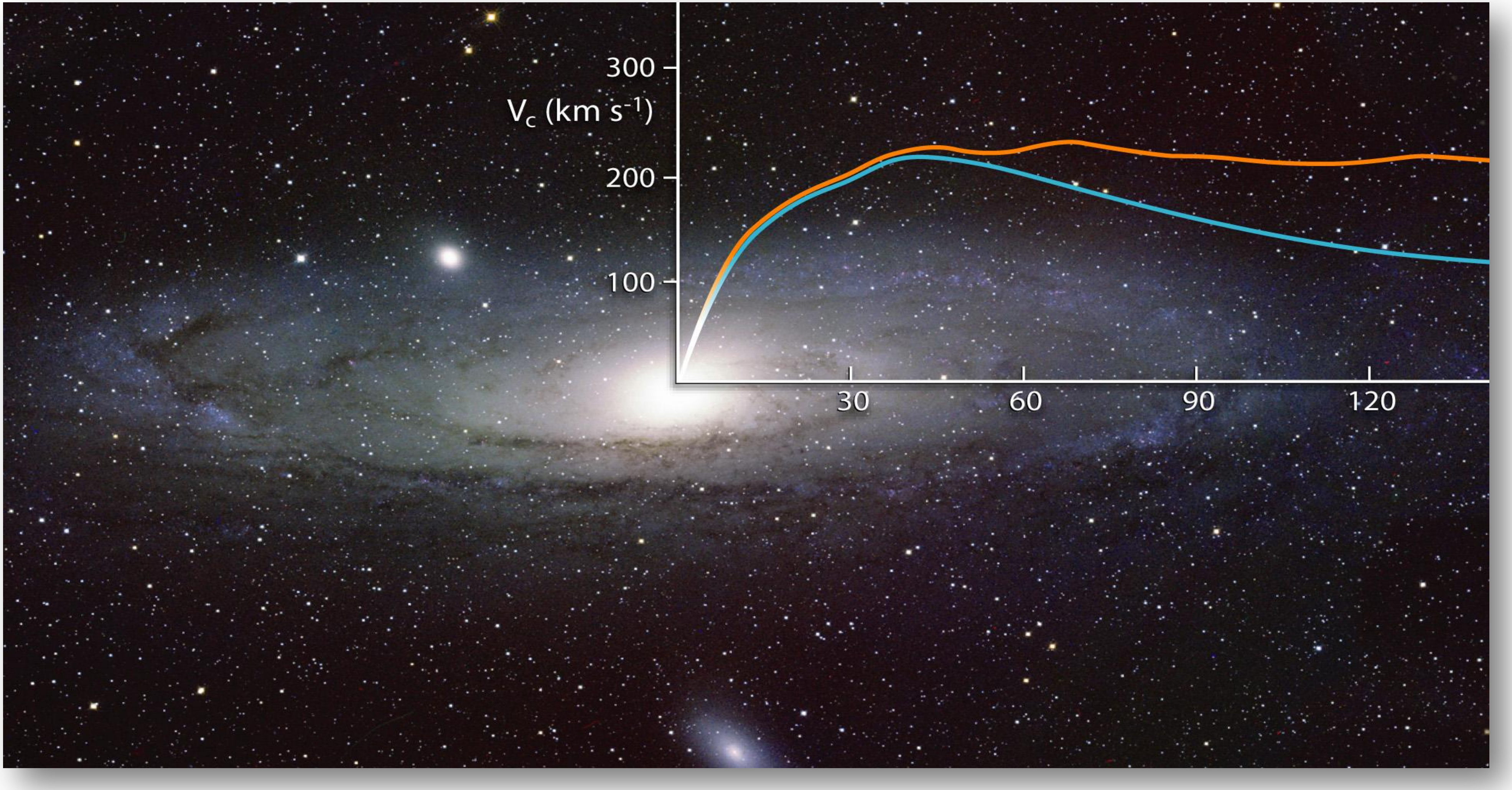
Stadel et al. 08

WIMP signals from very large number of very dense subhalos

To resolve the DM phenomenon with a cold particle has failed. Let’s now, instead hear what such a phenomenon has to reveal.

SPIRALS

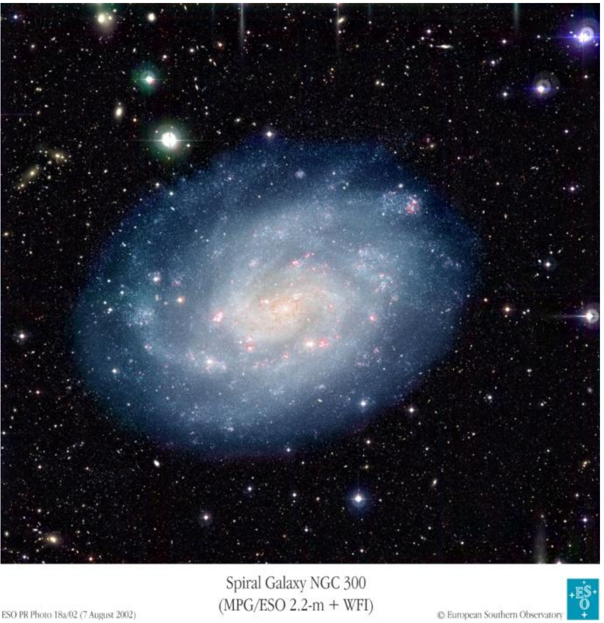
Primary crime scenes of the Dark Sector activities



Stellar Disks !!!

M33

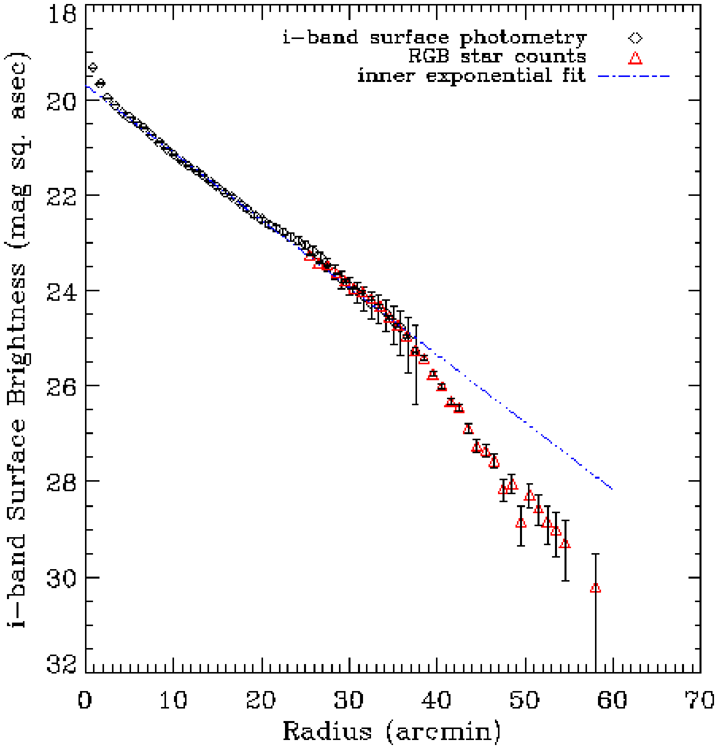
NGC 300



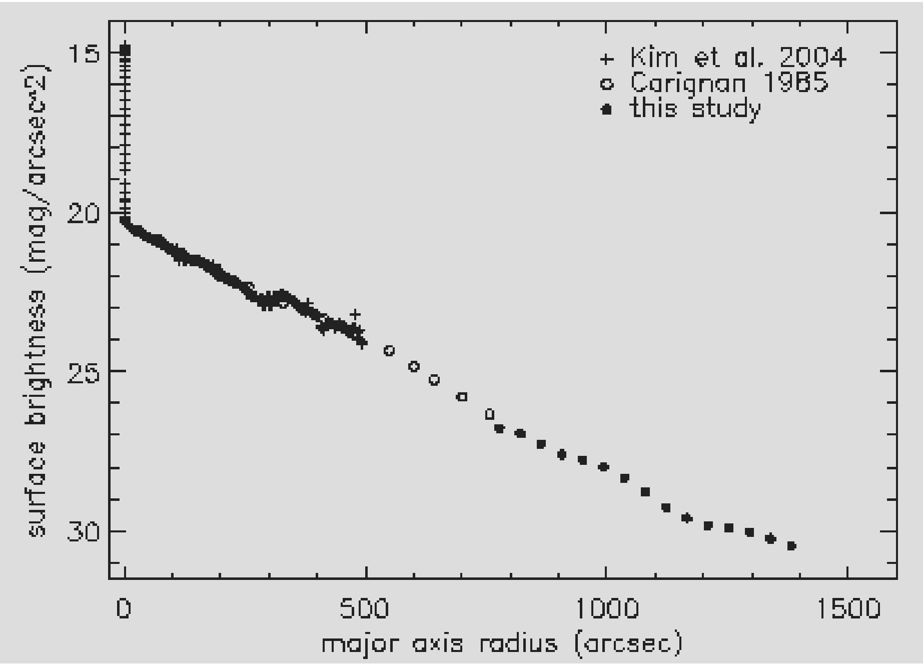
$$I(r) = I_0 e^{-r/R_D}$$

R_D lenght scale of the disk

Freeman, 1970

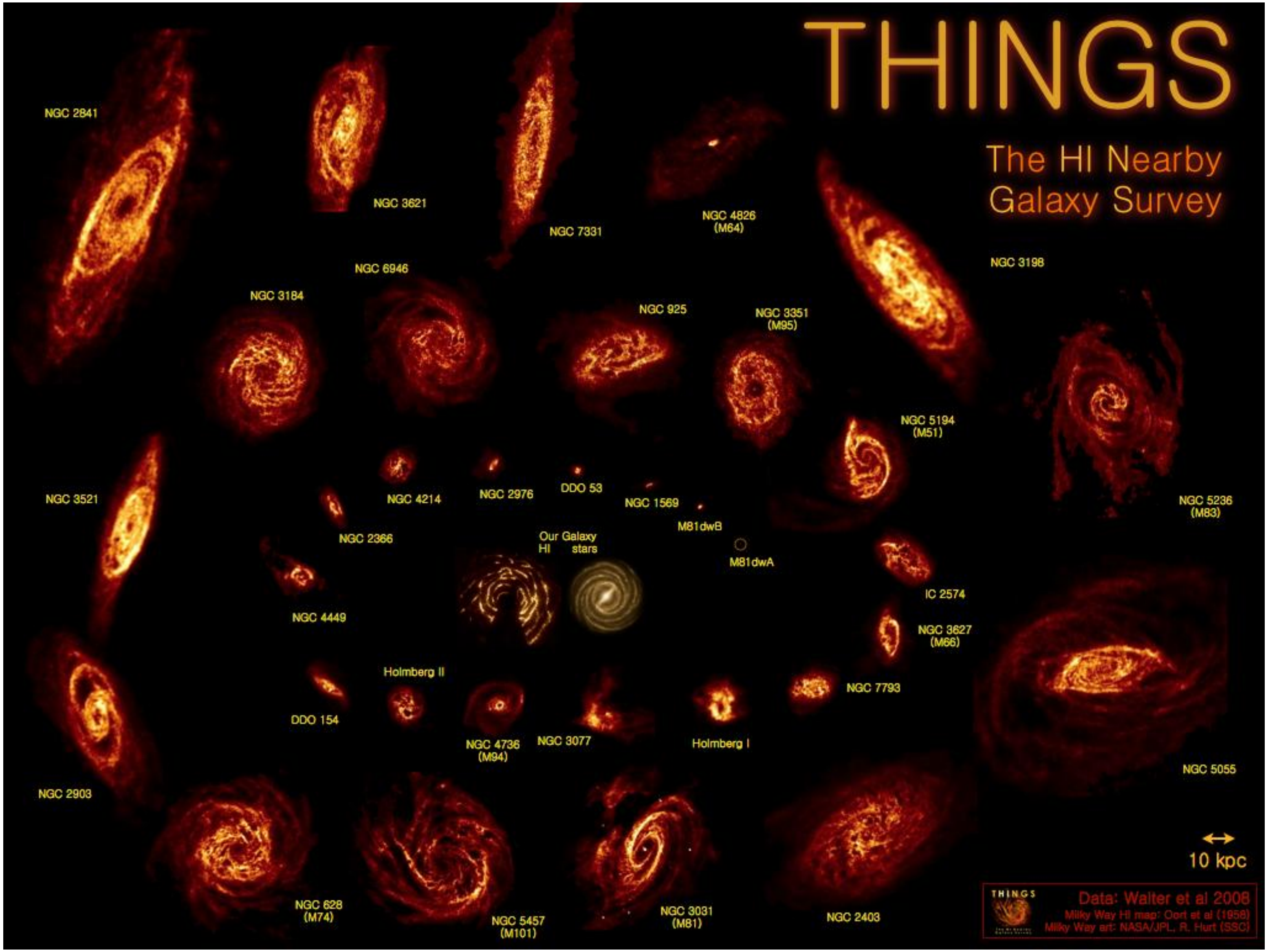


Ferguson et al 2003



Bland-Hawthorn et al 2005

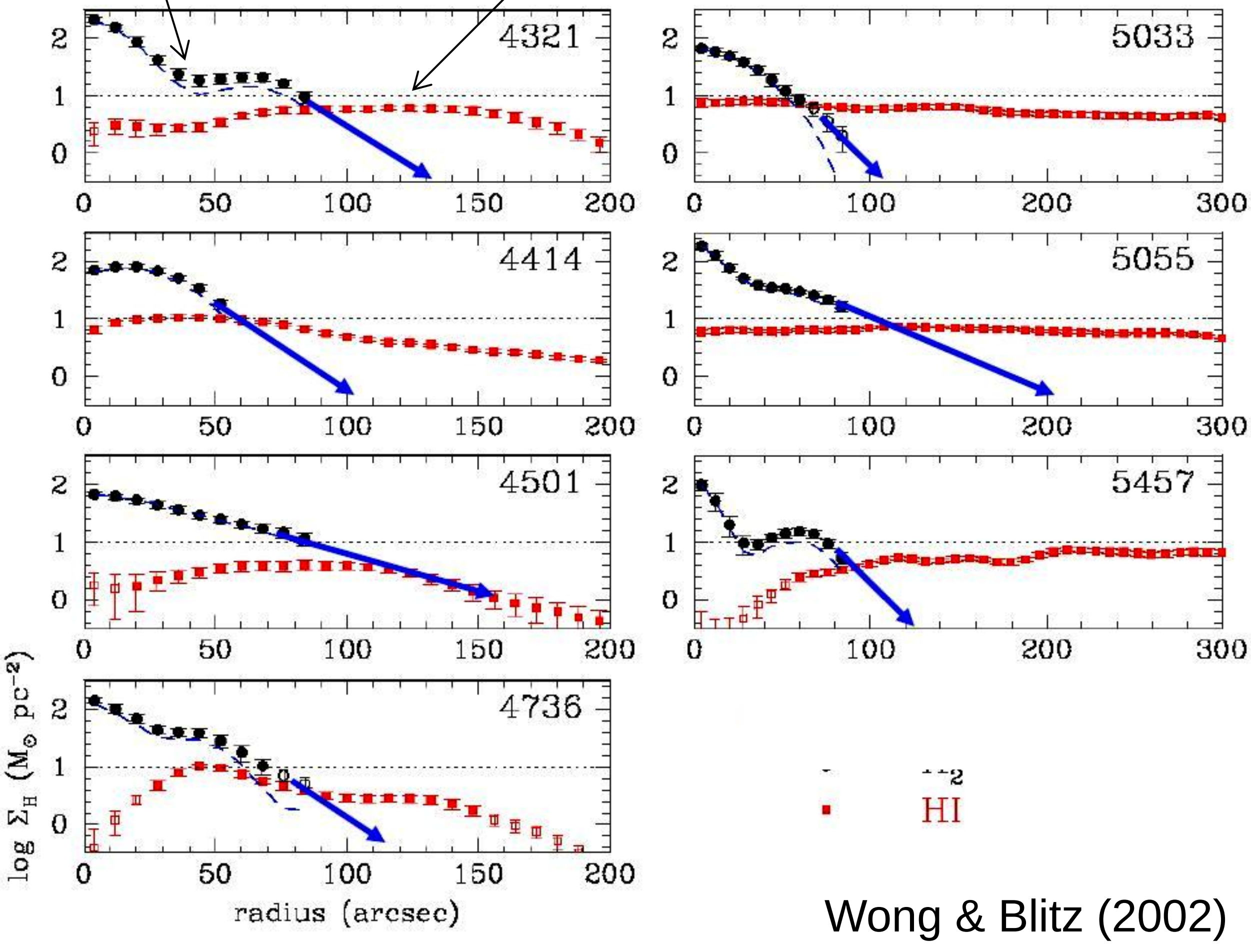
Large gaseus disks



HI surface densities Extended to (8 – 40) R_D

STARS

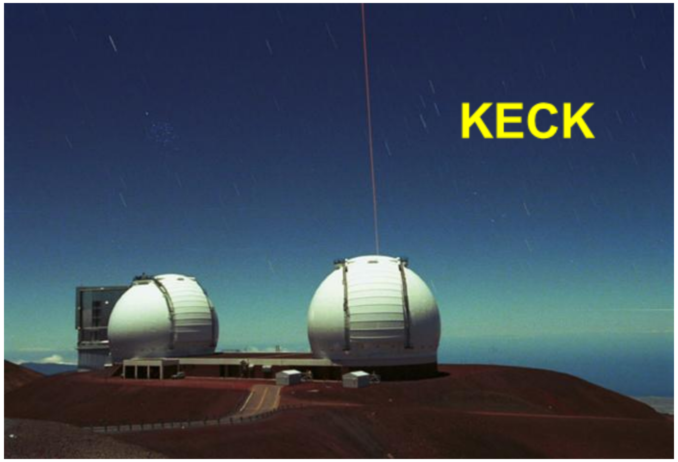
HI

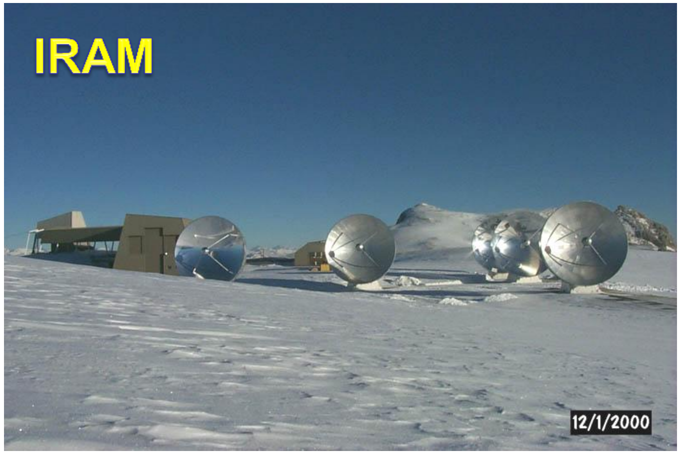


Wong & Blitz (2002)

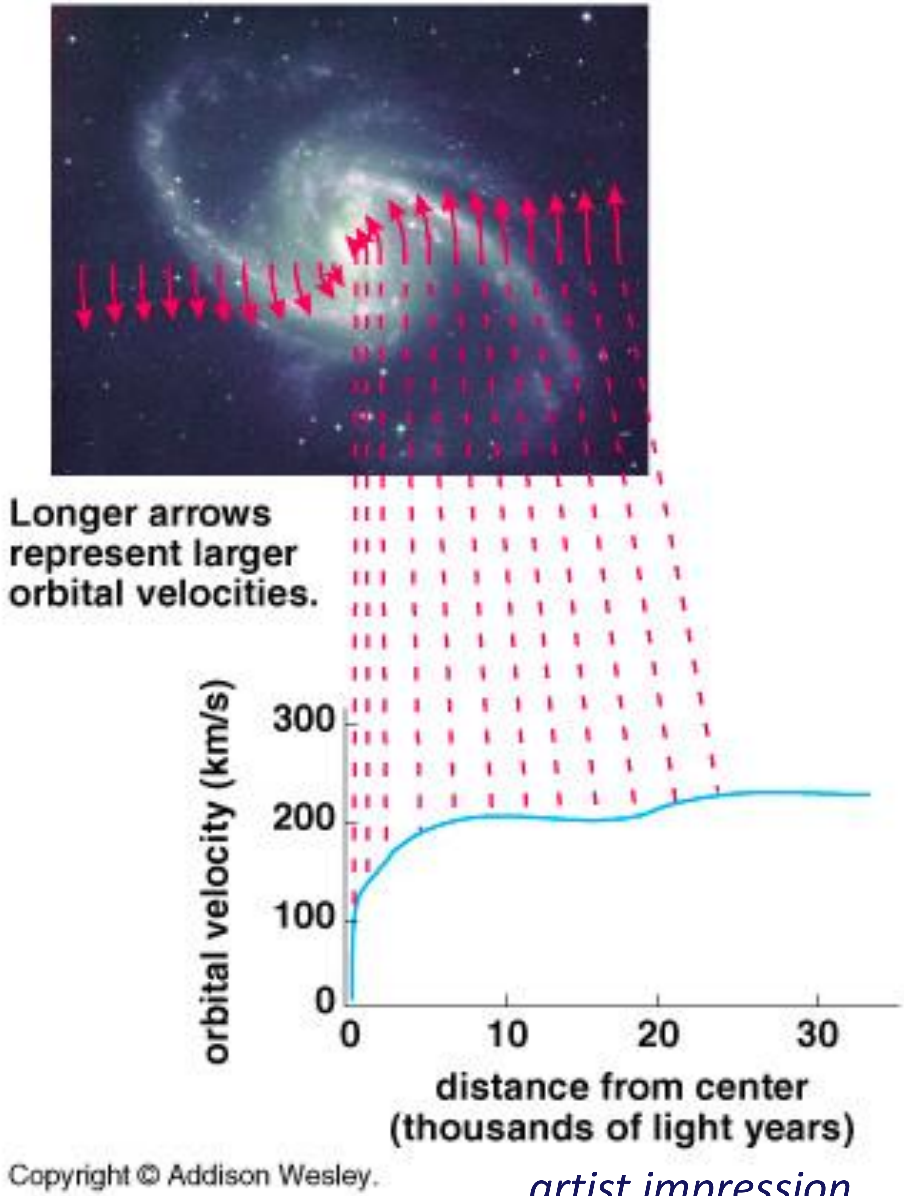
Circular velocities from spectroscopy

- Optical emission lines ($H\alpha$, Na)
- Neutral hydrogen (HI)-carbon monoxide (CO)



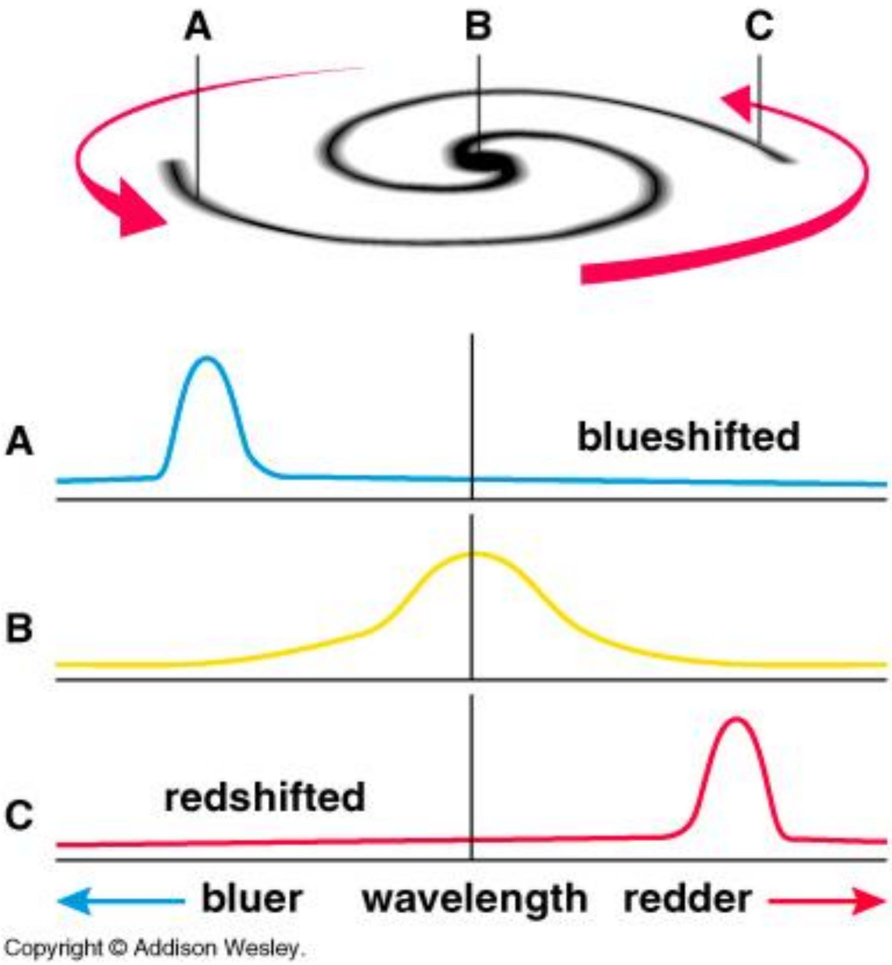


ROTATION CURVES



artist impression

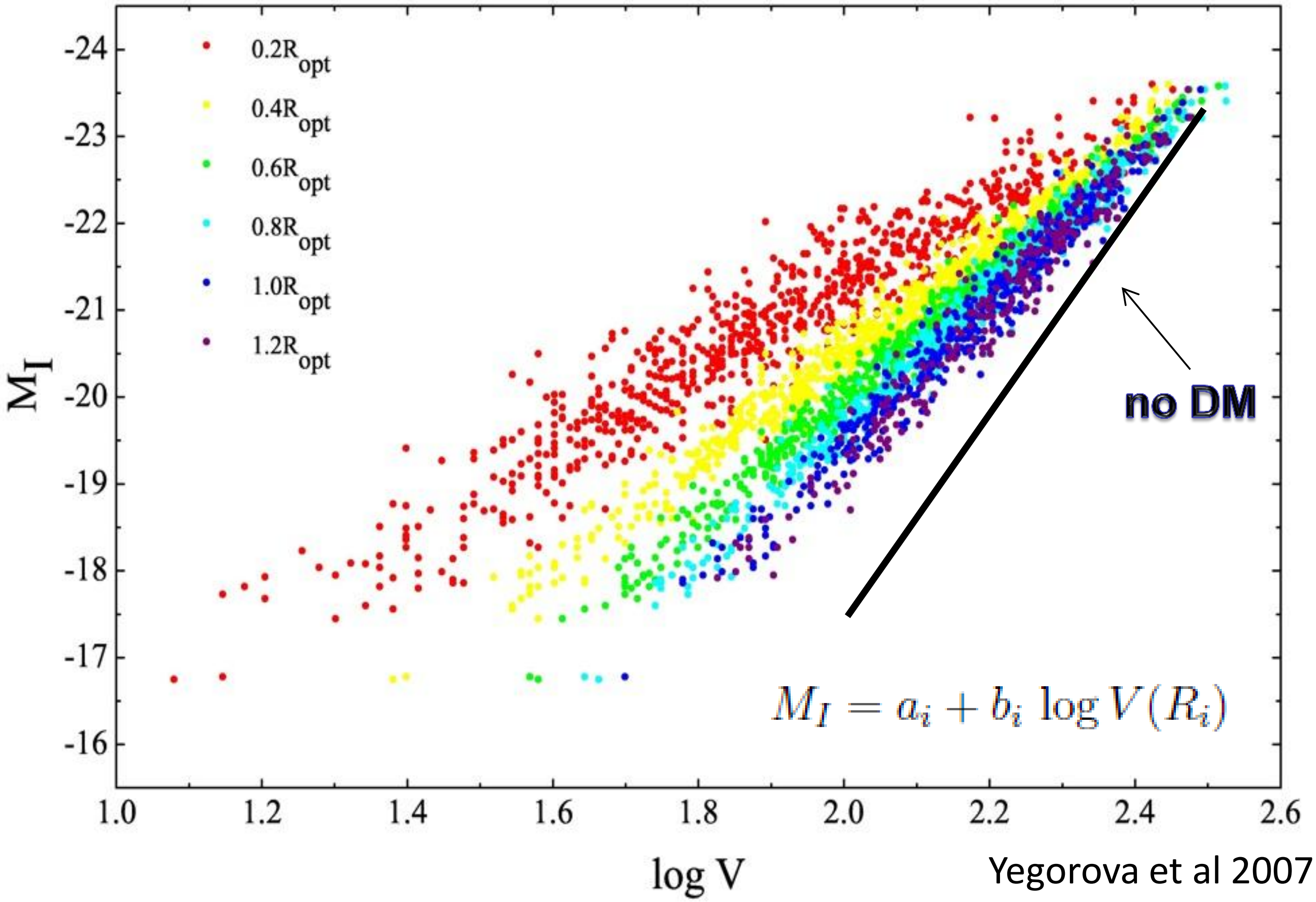
artist impression



Evidence for a Mass Discrepancy in Galaxies

The distribution of gravitating matter, unlike the luminous one, is luminosity dependent.

Tully-Fisher relation exists at local level (radii R_i)

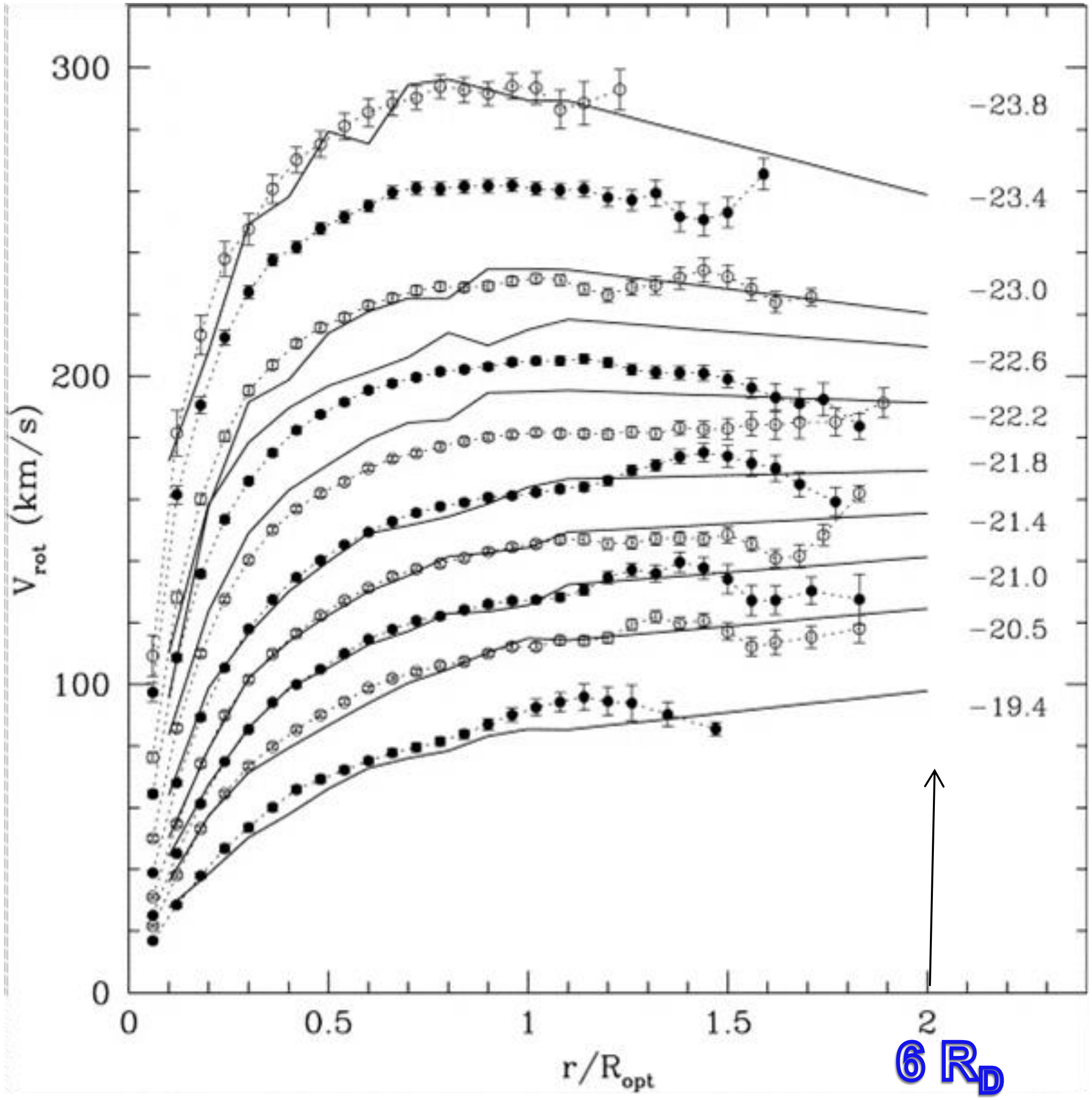


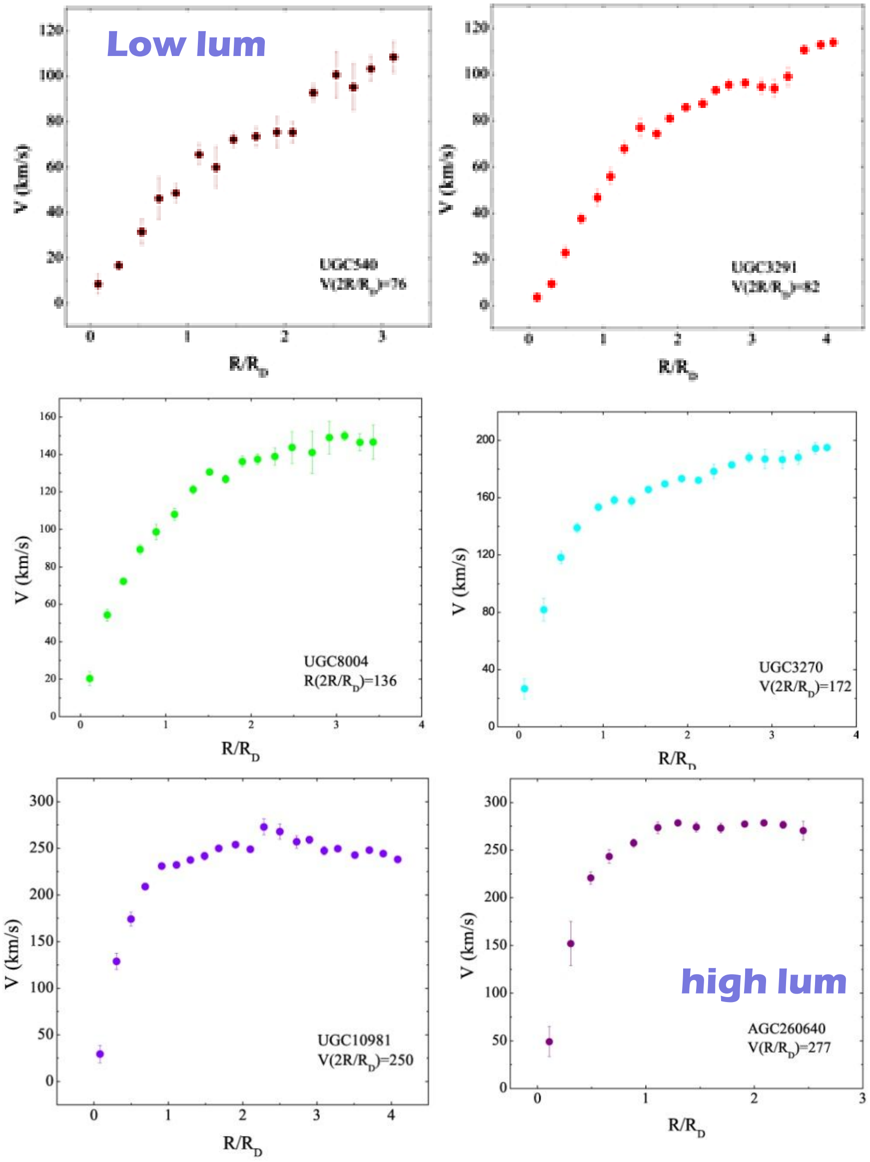
Yegorova et al 2007

Rotation Curves

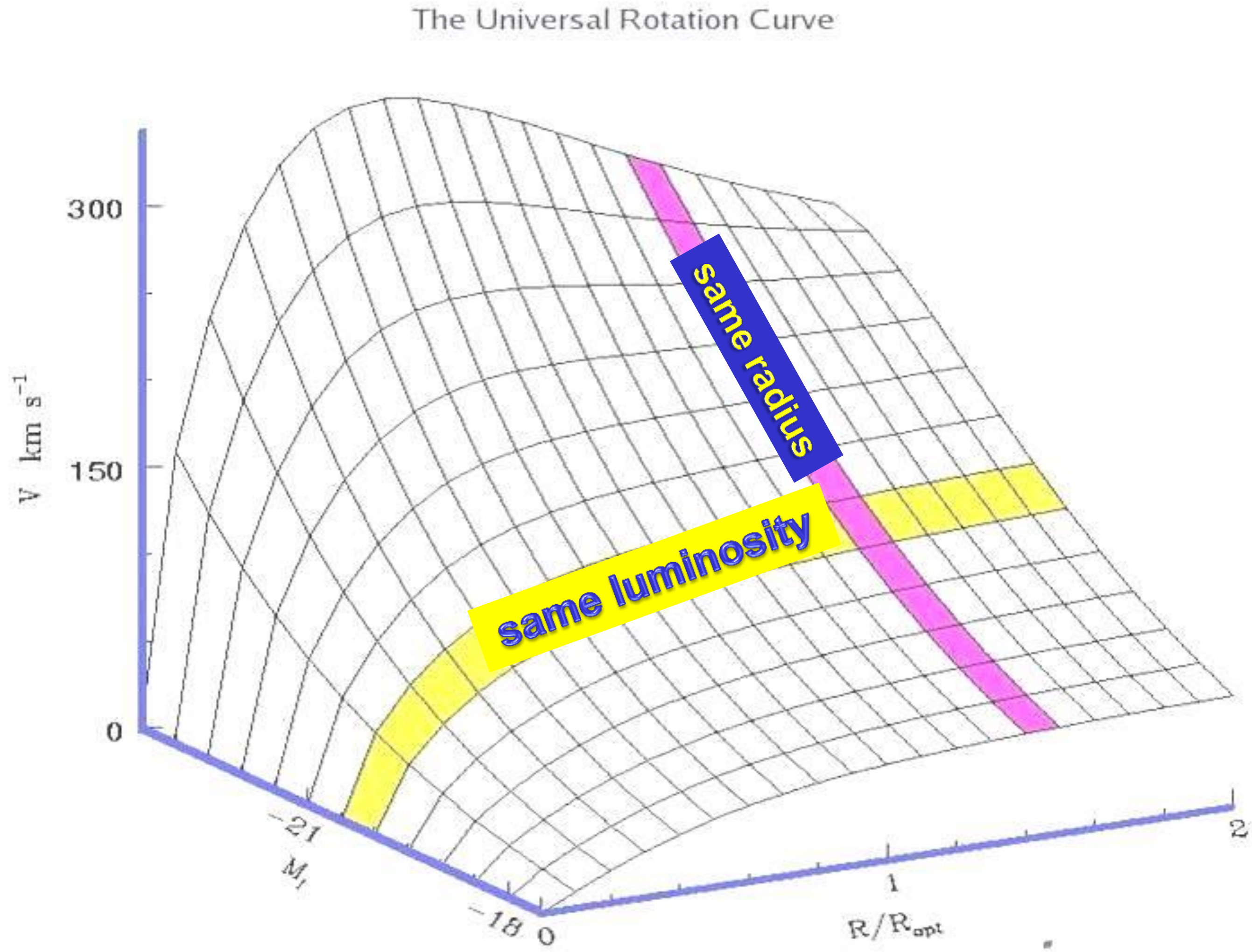
TYPICAL INDIVIDUAL RCs OF INCREASING LUMINOSITY

Coadded from 3200 individual RCs



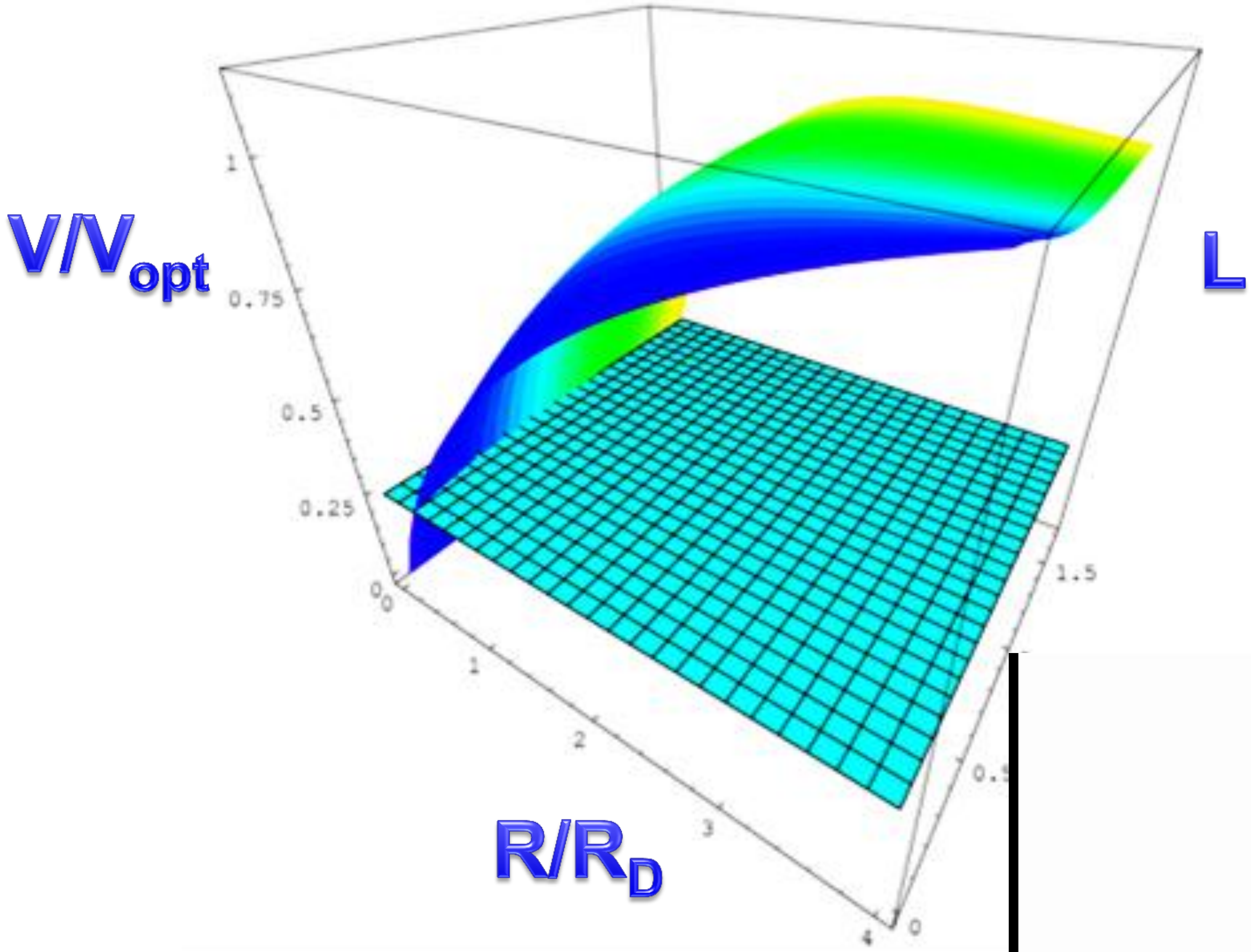


The Cosmic Variance of V measured in galaxies of same luminosity L at the same radius $x=R/R_D$ is negligible compared to the variations that V shows as x and L varie.



The Concept of the Universal Rotation Curve (URC)

Every RC can be represented by: V(x,L) x=R/R_D



Movie at: people.sissa.it/~salucci/DMAW2010/IMG_014.MOV

From data to mass models

$$V^2(R) = V^2_{halo}(R) + V^2_{HI}(R) + V^2_{disk}(R)$$

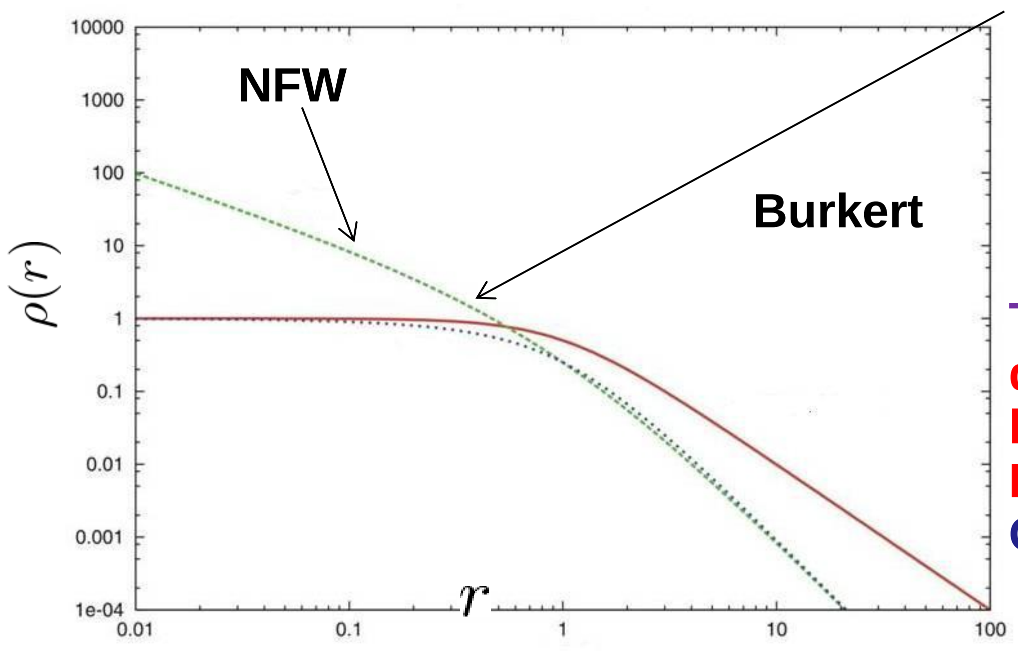
observations = model

- V^2_{disk} **from I-band photometry**
- V^2_{HI} **from HI observations**
- V^2_{halo} **from different choices for the DM halo density**

Dark halos with central constant density (Burkert, Isothermal)

Dark halos with central cusps (NFW, Einasto)

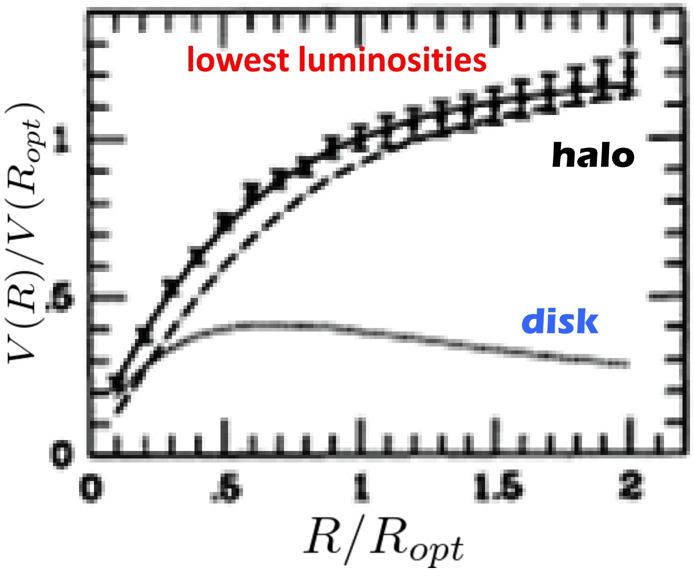
$$\rho(r) = \frac{\rho_0}{(1 + r/r_0)(1 + (r/r_0)^2)}$$



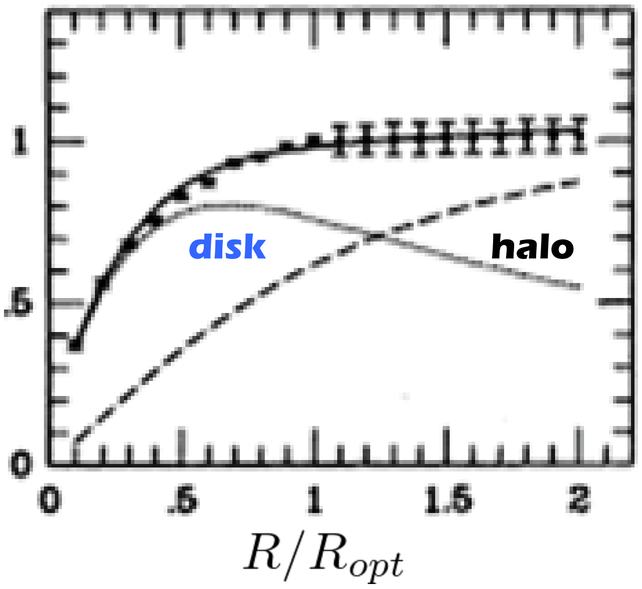
The mass model has 3 free parameters:
disk mass
halo central density
Halo core radius (length-scale)
Obtained by best fitting method

MASS MODELLING

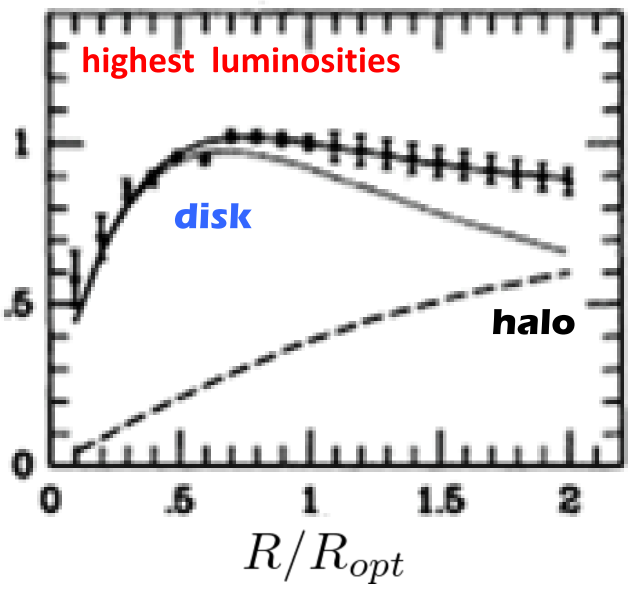
$M_I = -18$

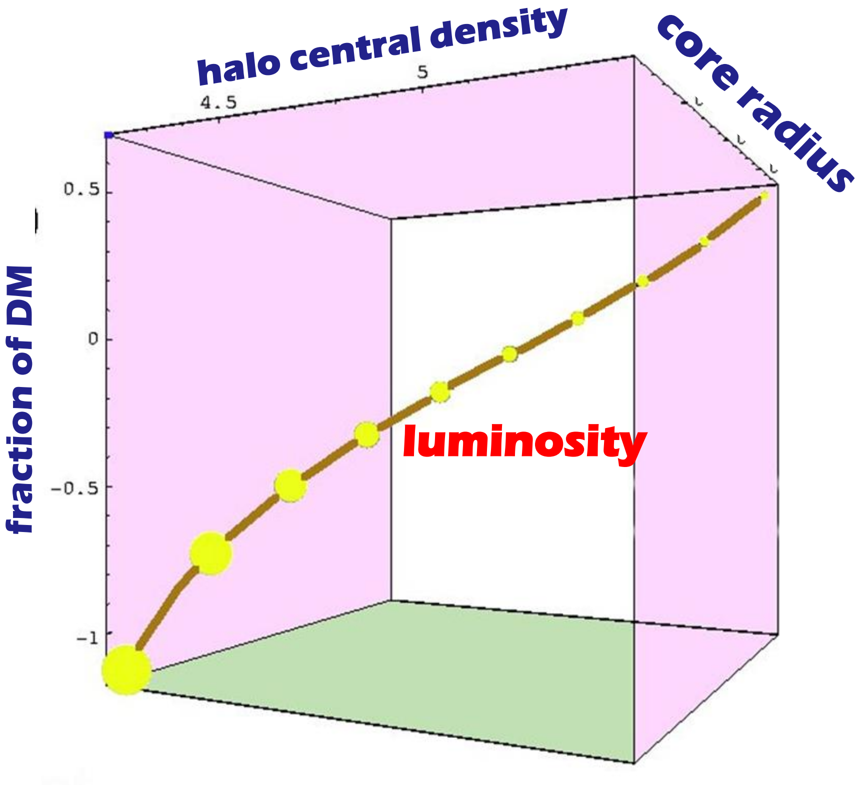


$M_I = -21$



$M_I = -23$

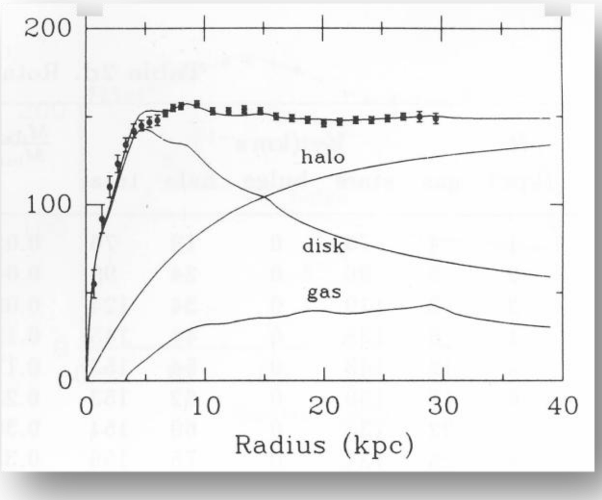




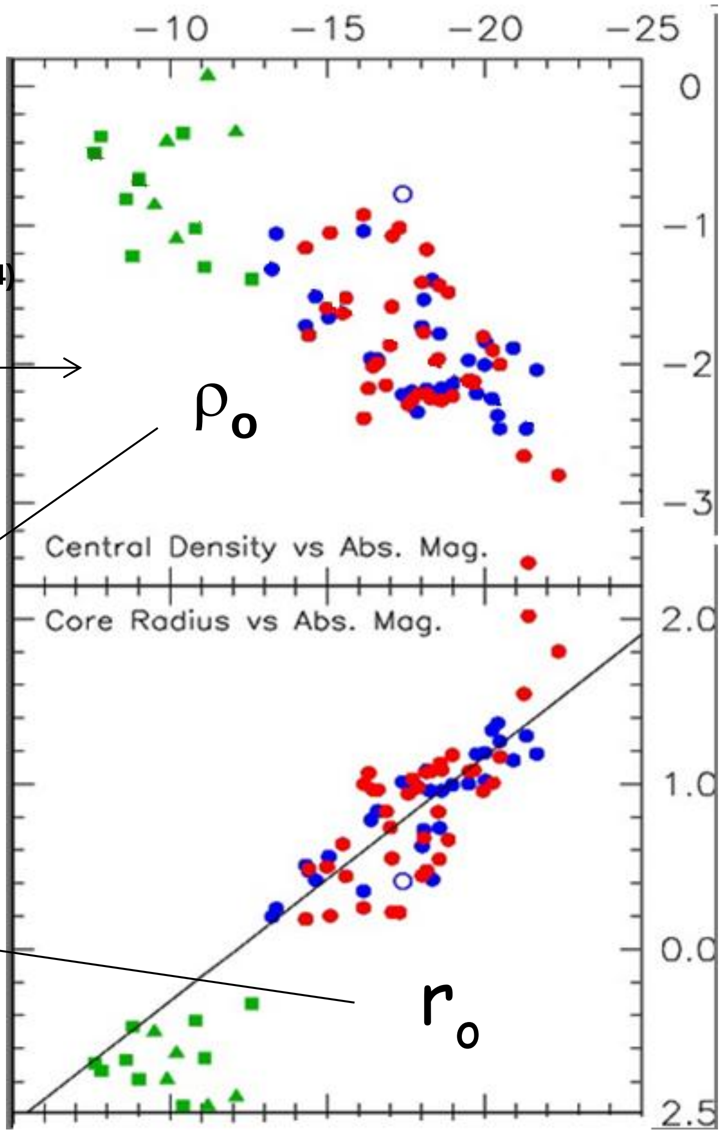
All DM and LM structural parameters are related with luminosity.

Dark Halo Scaling Laws in Spirals

Relationships between halo structural parameters (ρ_0, r_0) and luminosity by mass modelling individual galaxies



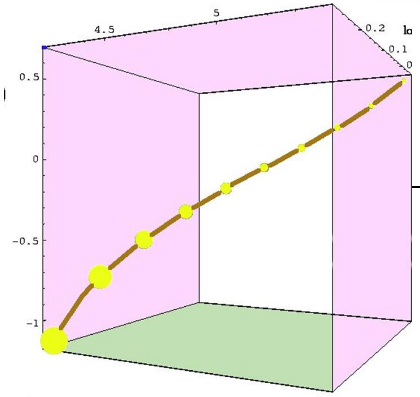
Kormendy & Freeman (2004)



ρ_o

r_o

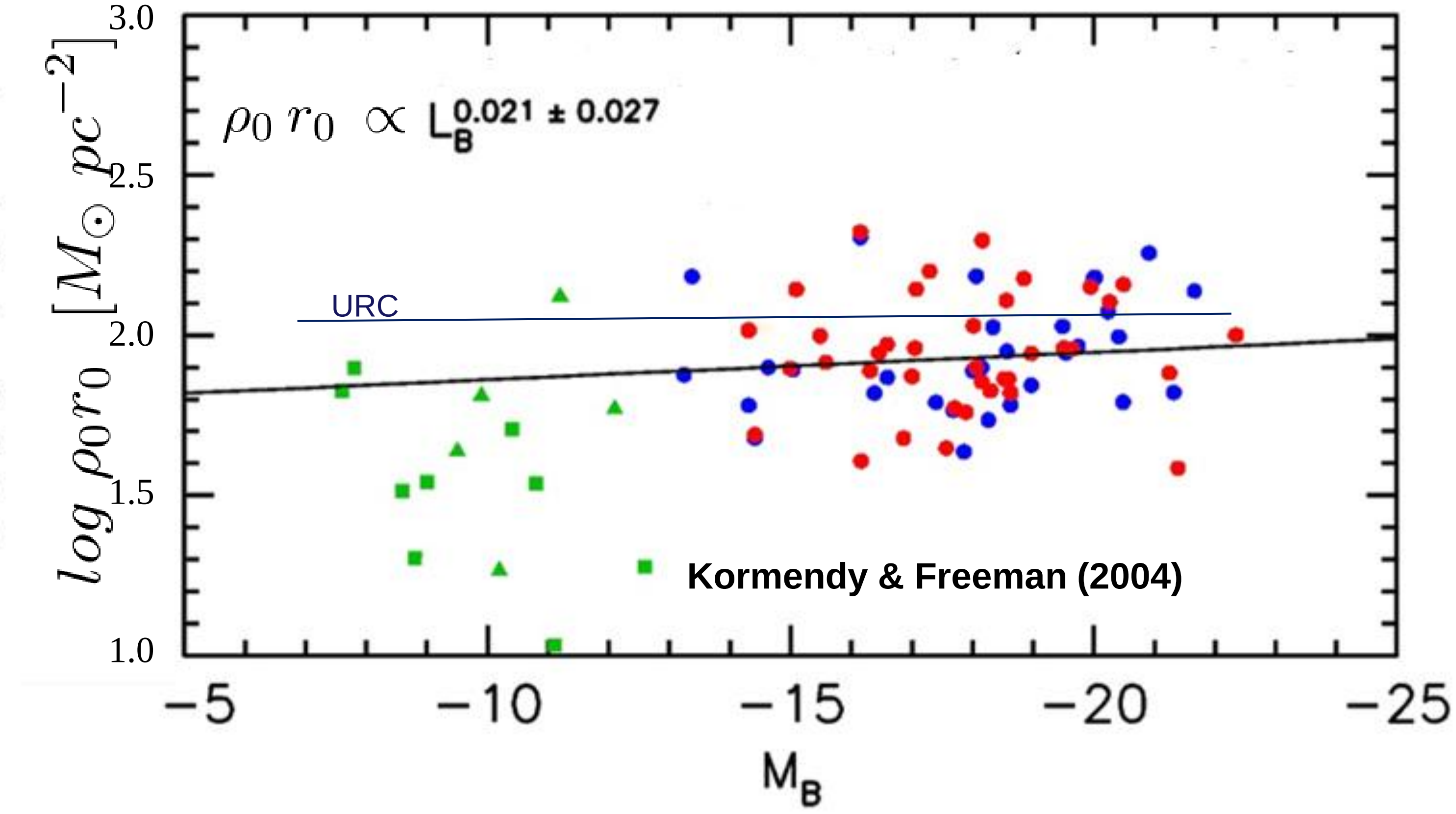
URC



$$\rho_o \sim L_I^{-0.7}$$
$$r_o \sim L_I^{0.7}$$

$$\rho_o \sim L_B^{-0.6}$$
$$r_o \sim L_B^{0.6}$$

The halo central surface density $\rho_0 r_0$: constant in Spirals

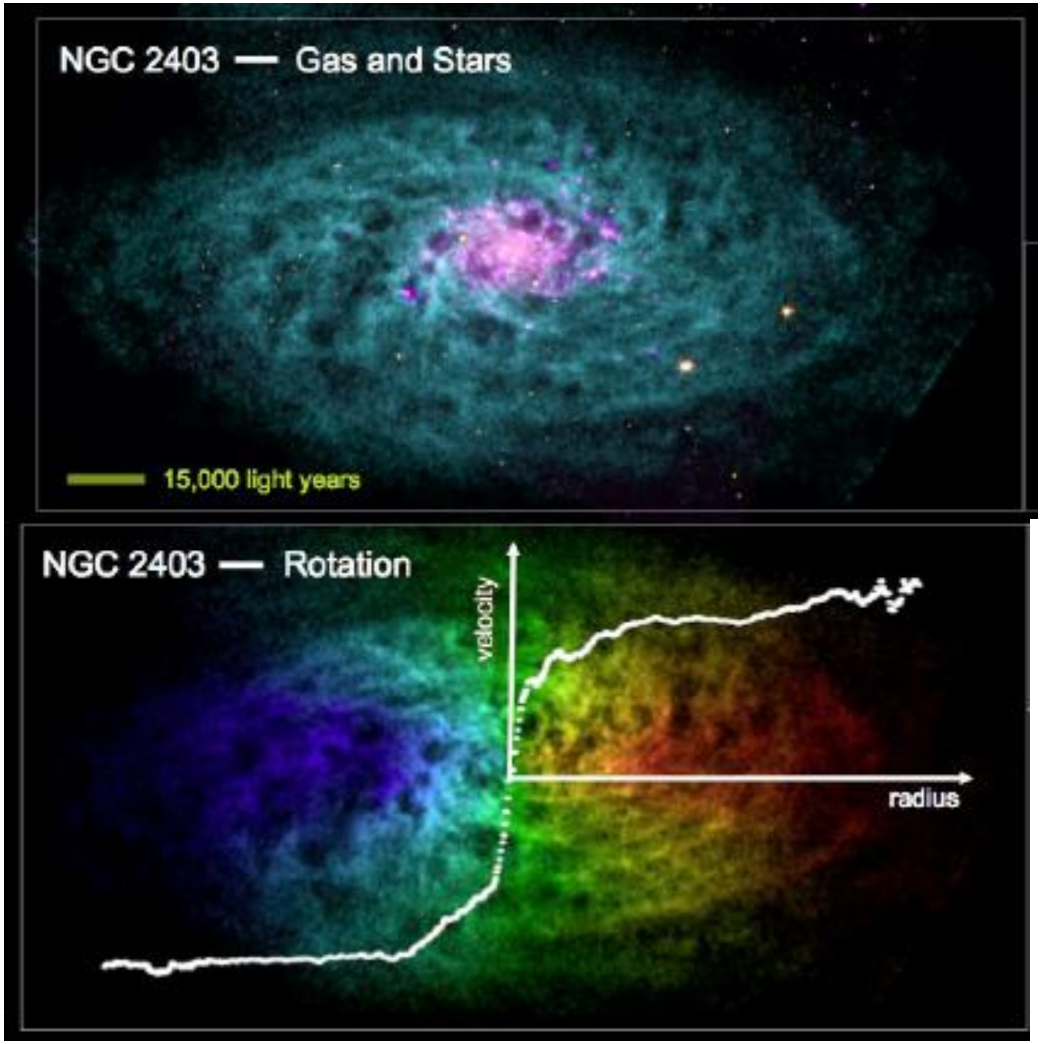


The distribution of DM around spirals

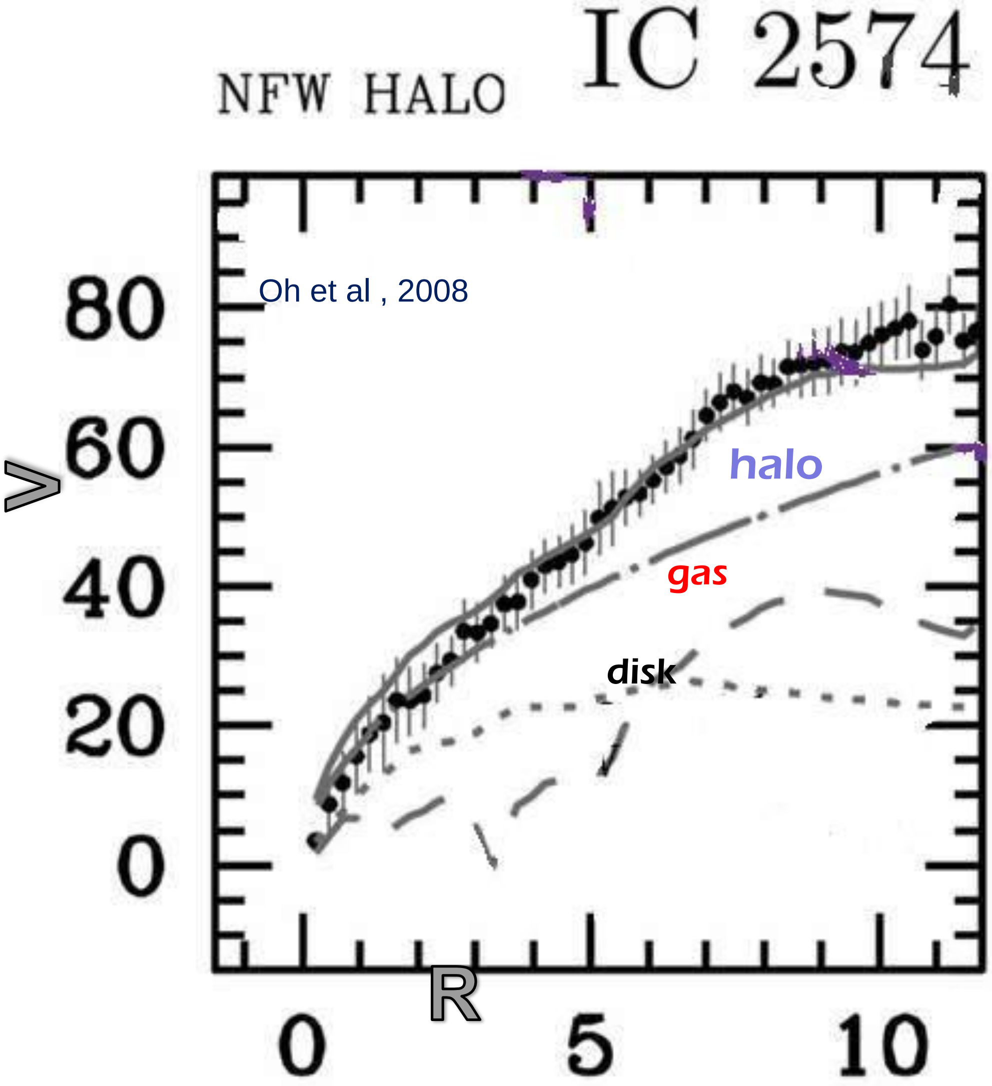
Individual galaxies objects

Gentile+ 2004, de Blok+ 2008 Kuzio de Naray+ 2008, Oh+ 2008, Spano+ 2008, Trachternach+ 2008, Donato+,2009

Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey

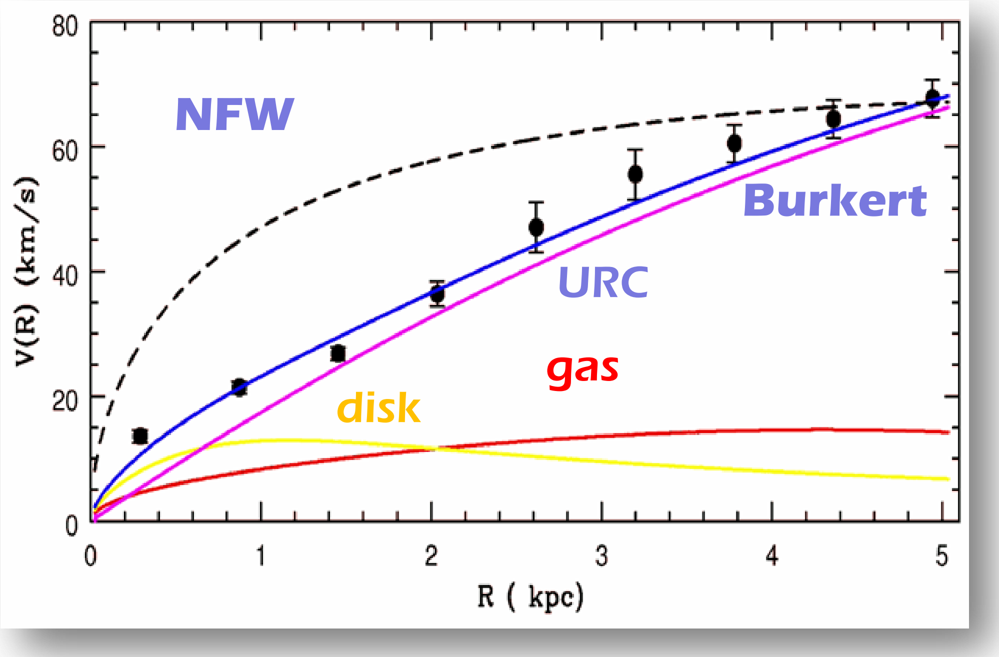


DISAGREEMENT



DDO 47

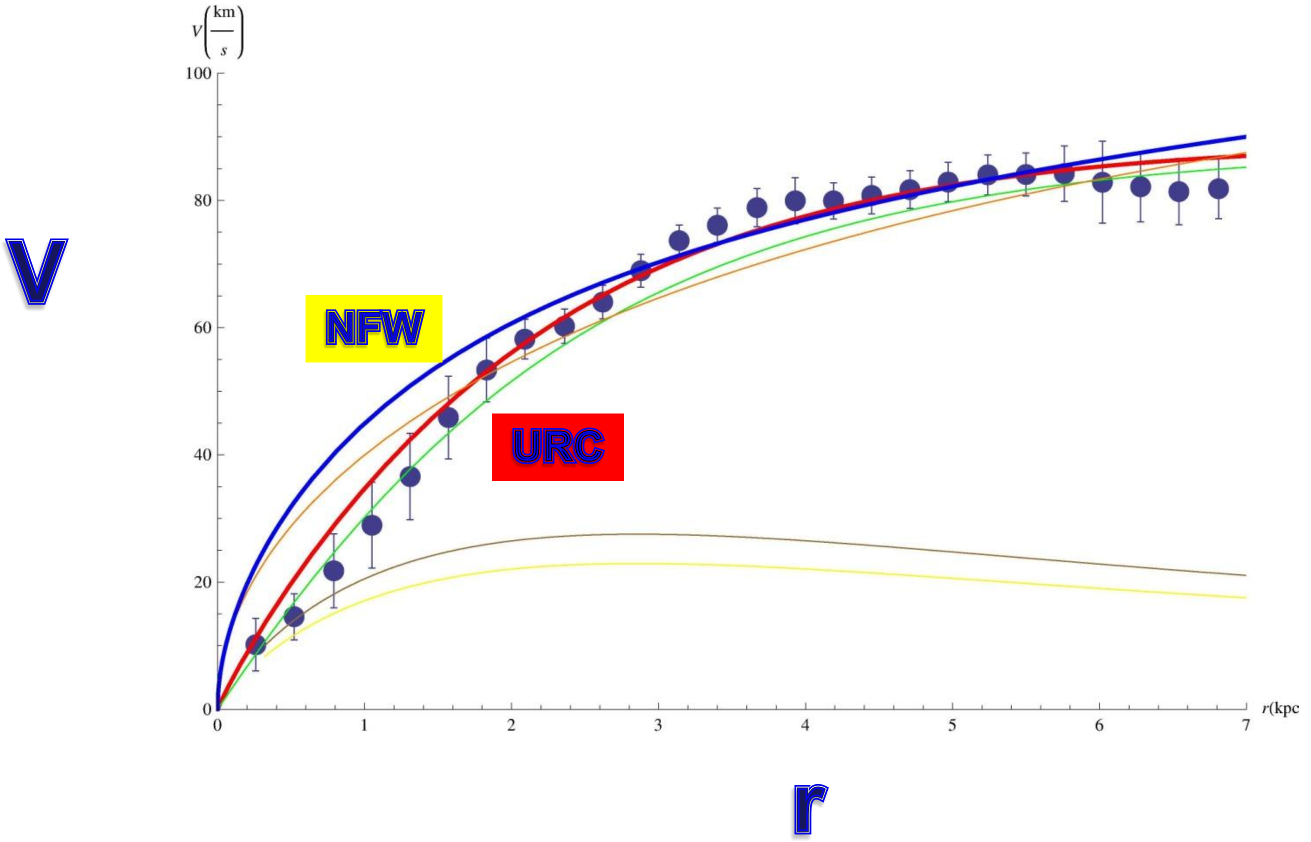
Gentile et al 2005



- **Non-circular motions are small.**
- **URC halos ok NFW not**

NOTE: Tri-axiality and non-circular motions cannot explain the CDM/NFW cusp/core discrepancy

ORION DWARF



ELLIPTICALS

Where hungry monsters lurk among the stars

The Stellar Spheroid

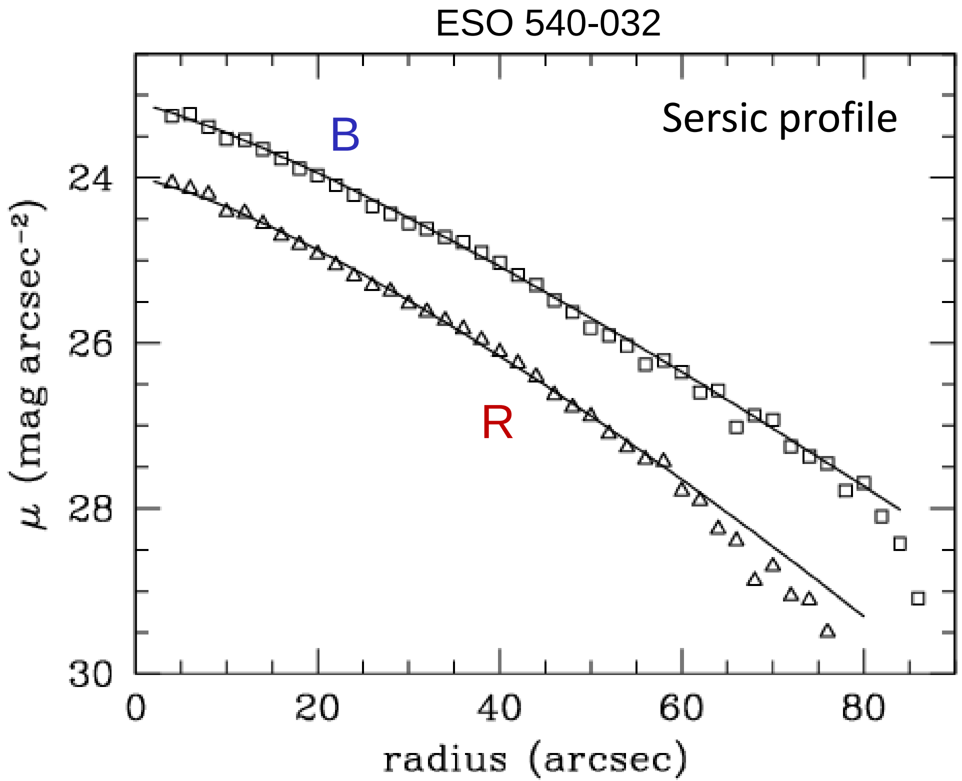
Surface brightness of ellipticals follows a Sersic (de Vaucouleurs) law

$$I(R) = I_e e^{-b_n[(R/R_e)^{1/n}-1]}$$

$\boldsymbol{R_e}$: the radius enclosing half of the projected light.

By deprojecting I(R) we obtain the luminosity density *j(r)*:

$$I(R) = \int_{-\infty}^{+\infty} j(r)\,dz = 2\int_{R}^{+\infty} \frac{j(r)\,r\,dr}{\sqrt{r^2 - R^2}} \qquad \rho_{sph}(r) = (M/L)_{\star}\, j(r)$$


ESO 540-032

Modelling Ellipticals

Measure the light profile = stellar mass profile $(M_*/L)^{-1}$

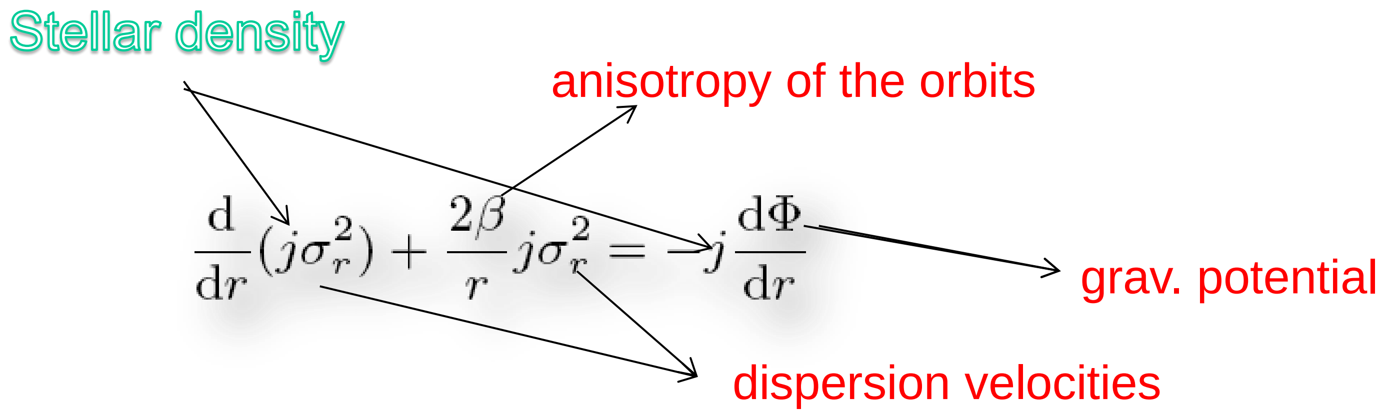
Derive the total mass profile M(r) from:

Dispersion velocities of stars or of Planetary Nebulae

X-ray properties of the emitting hot gas

Disentangle M(r) into its dark and the stellar components

Gravity is balanced by pressure gradients -> Jeans Equation



Stellar density

anisotropy of the orbits

$$\frac{\mathrm{d}}{\mathrm{d}r}(j\sigma_r^2) + \frac{2\beta}{r} j\sigma_r^2 = -j\frac{\mathrm{d}\Phi}{\mathrm{d}r}$$

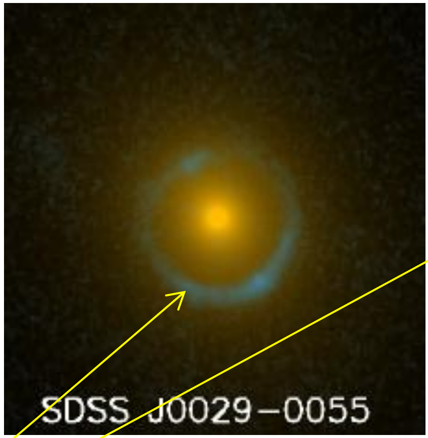
grav. potential

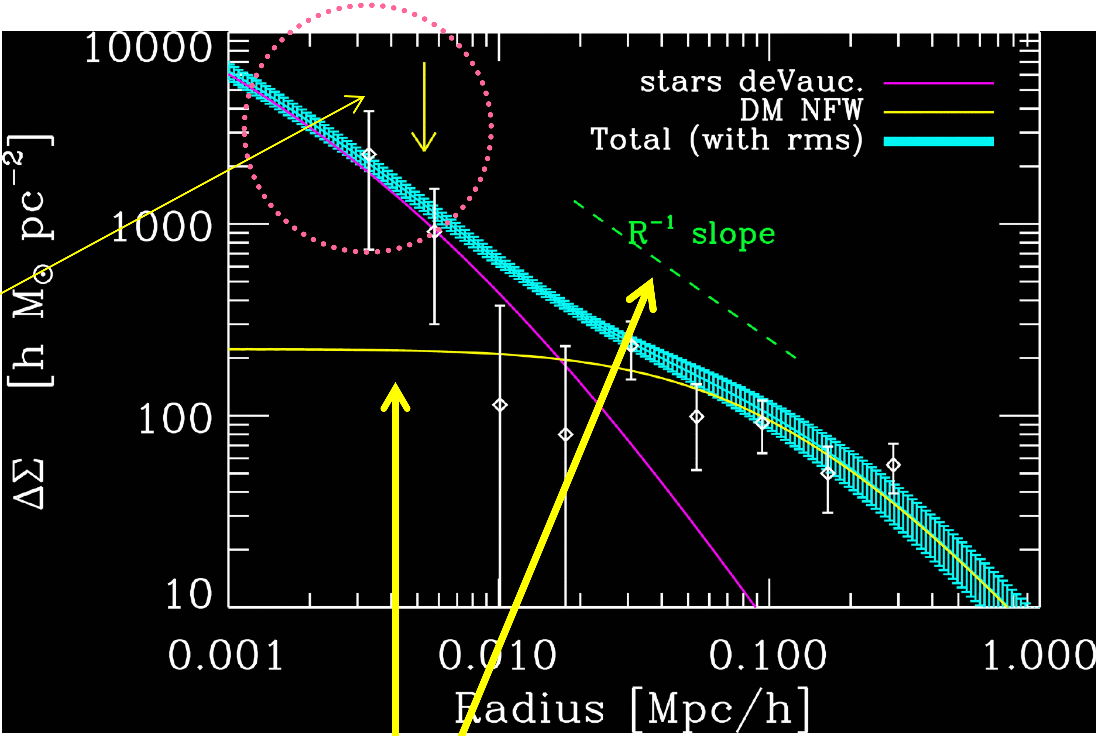
dispersion velocities

Weak and strong lensing

SLACS: Gavazzi et al. 2007)

strong lensing measures the **total** mass inside the Einstein ring





AN EINSTEIN RING AT $\mathbf{R}_{\mathbf{einst}}$ IMPLIES THERE A CRITICAL SURFACE DENSITY:

$$\Sigma(R_{Einst}) = \frac{0.35}{D\ (Gpc)}\ g/cm^2$$

D = $\frac{D_{\mathrm{os}}}{D_{\mathrm{ol}}D_{\mathrm{ls}}}$

,

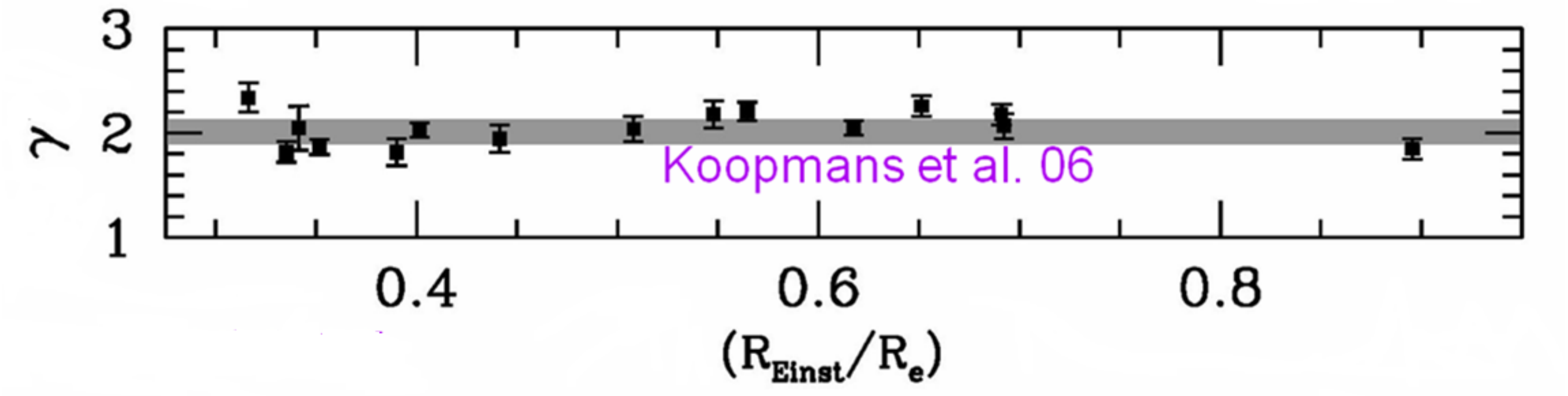
DISAGREEMENT

Strong lensing and galaxy kinematics

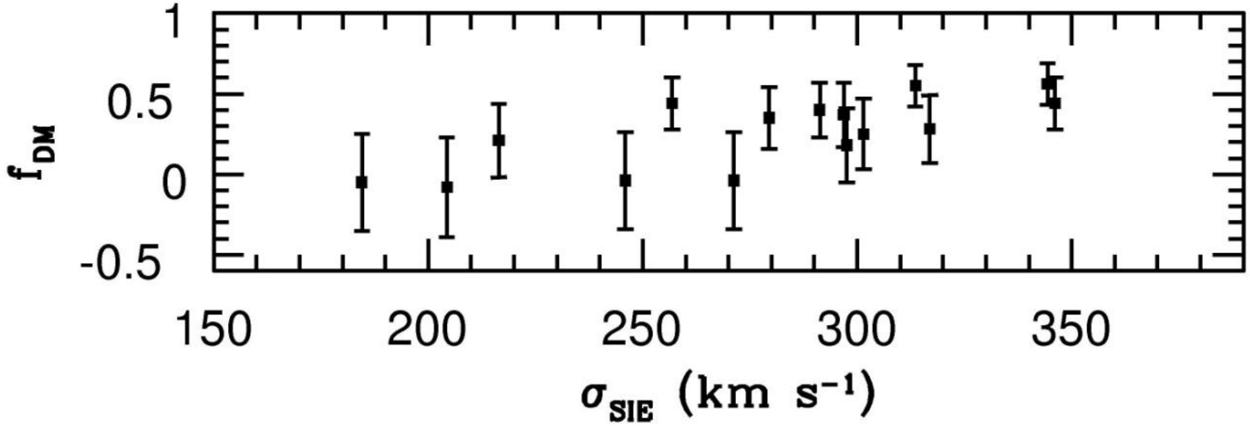
Koopmans, 2006

Assume $\rho_{tot}(r) = \rho_0(r/r_0)^\gamma$ $\rho_{sph}(r) = \frac{M_{sph}}{4\pi} \frac{R_e}{r(r+R_e/1.8)^3}$

Fit $M_{tot}(R_{Einst}), \sigma_{ap}(R)$



Inside R_{Einst} the total (spheroid + dark halo) mass increase proportionally with radius



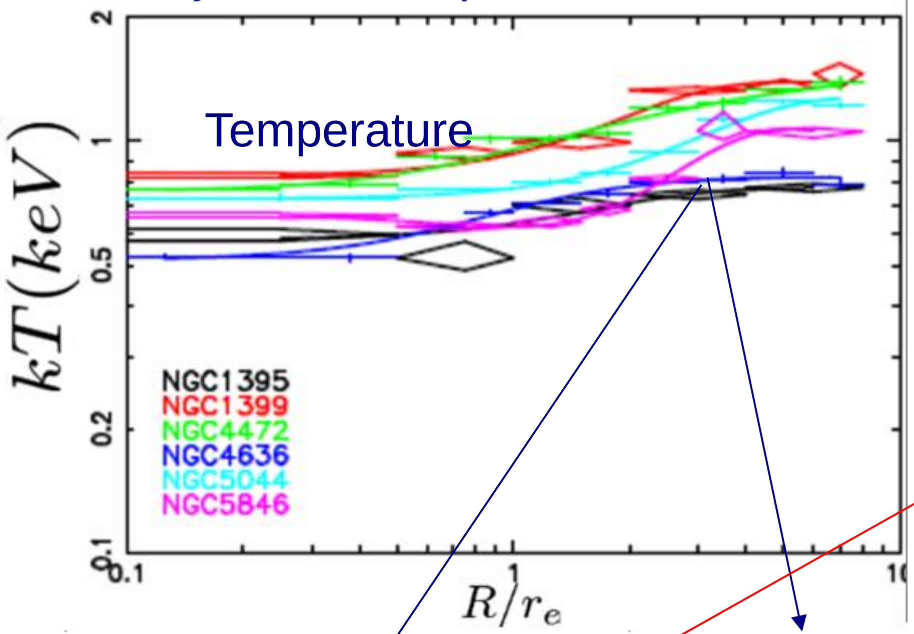
Inside R_{Einst} the total the fraction of dark matter is small

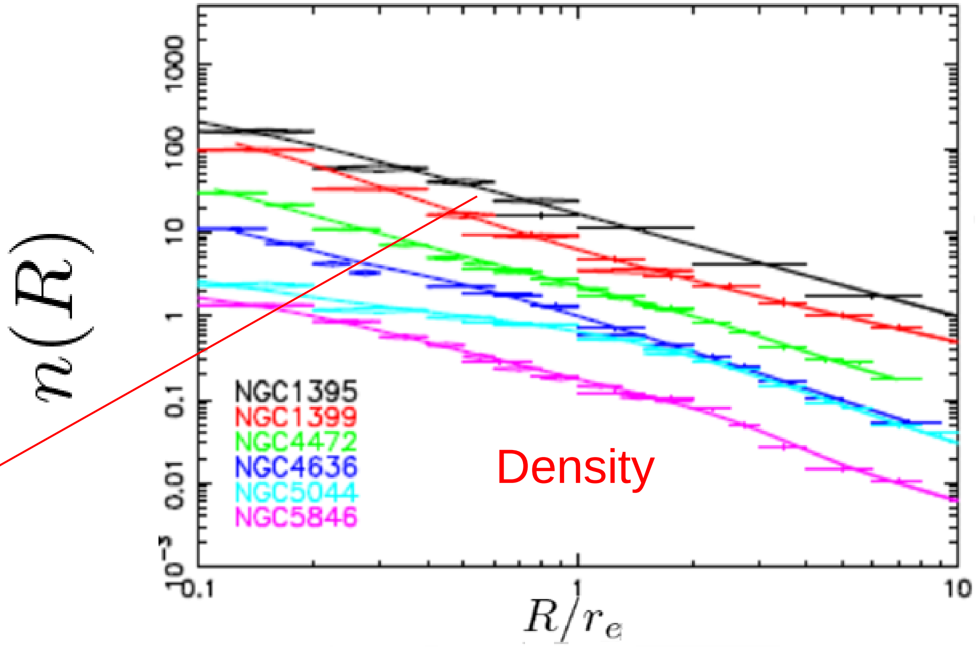
DM distribution is cored

Mass Profiles from X-ray

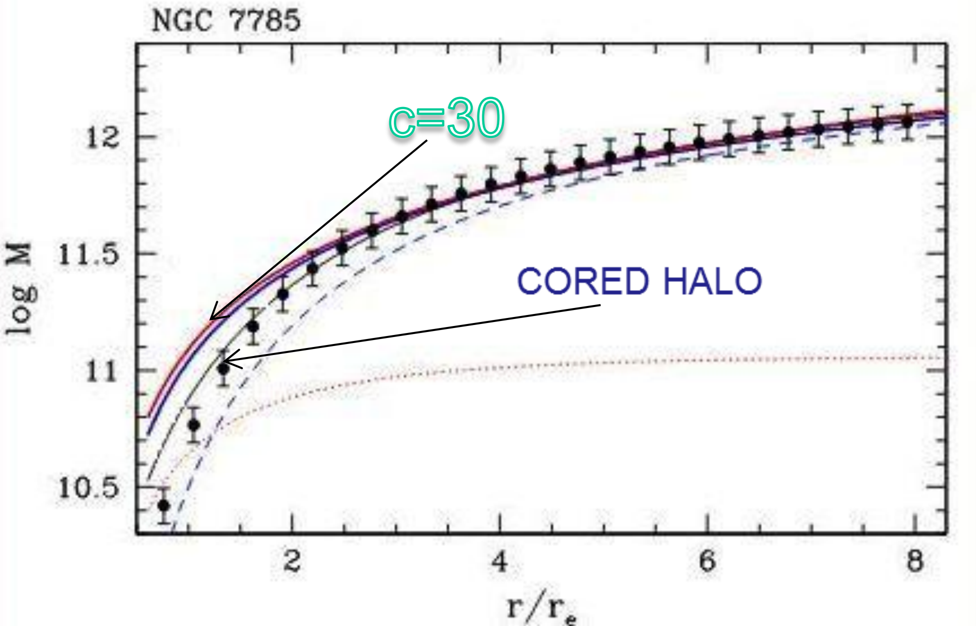
Nigishita et al 2009

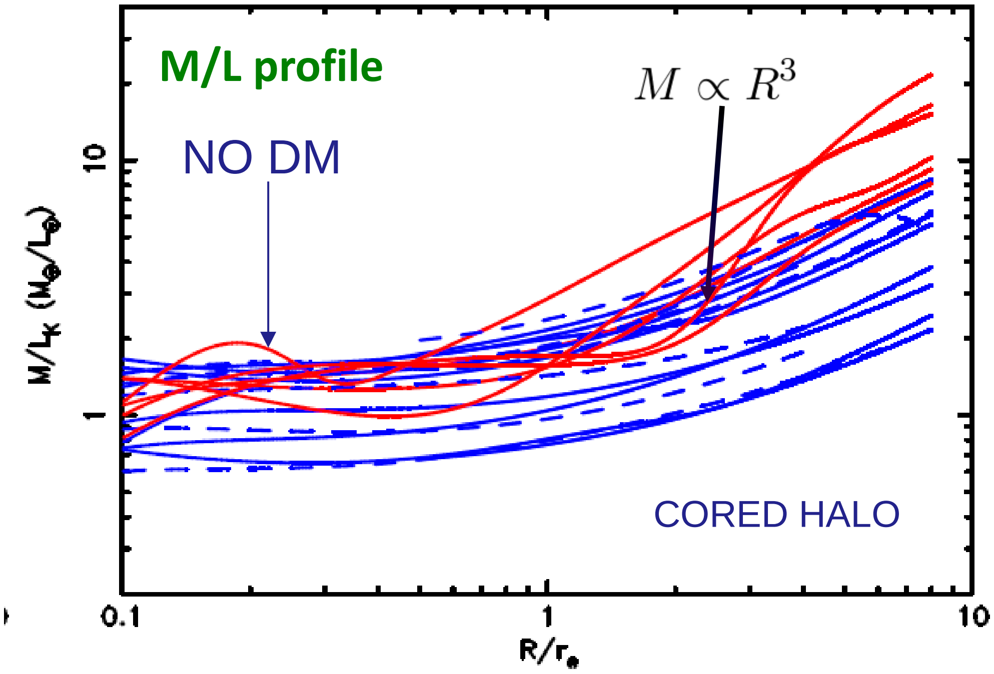
Hydrostatic Equilibrium





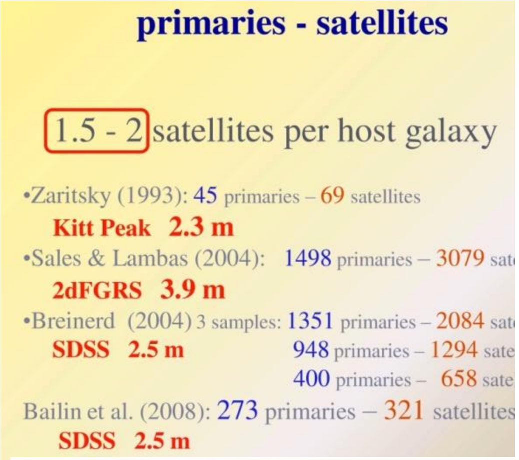
$$M(R) = -\frac{kT(R)\cdot R}{G\mu m_p}\left(\frac{d\ln n(R)}{d\ln R} + \frac{d\ln T(R)}{d\ln R}\right)$$





DM profile from spiral's satellites

Yegorova et ali, 2011,



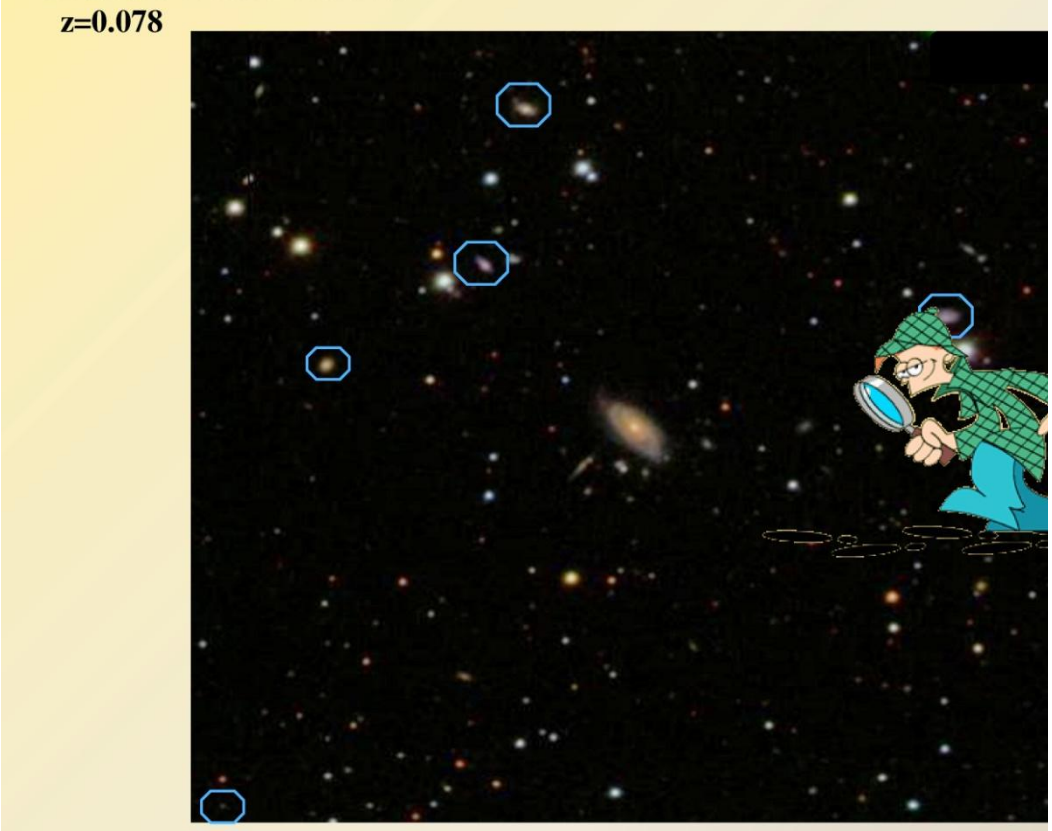
primaries - satellites

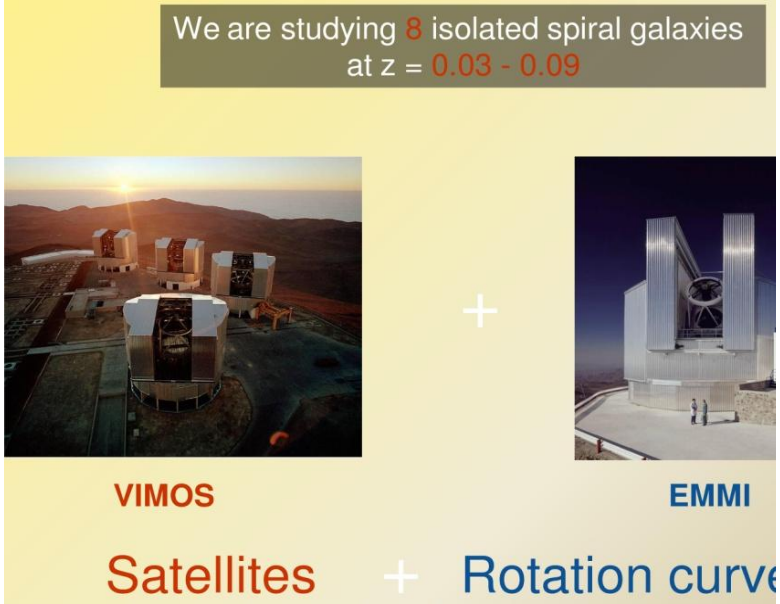
1.5 - 2 satellites per host galaxy

- Zaritsky (1993): 45 primaries – 69 satellites
  Kitt Peak 2.3 m
- Sales & Lambas (2004): 1498 primaries – 3079 sat
  2dFGRS 3.9 m
- Breinerd (2004) 3 samples: 1351 primaries – 2084 sat
  SDSS 2.5 m 948 primaries – 1294 sate
  400 primaries – 658 sate

Bailin et al. (2008): 273 primaries – 321 satellites
SDSS 2.5 m

SDSS J154040.56-000933.5
z=0.078



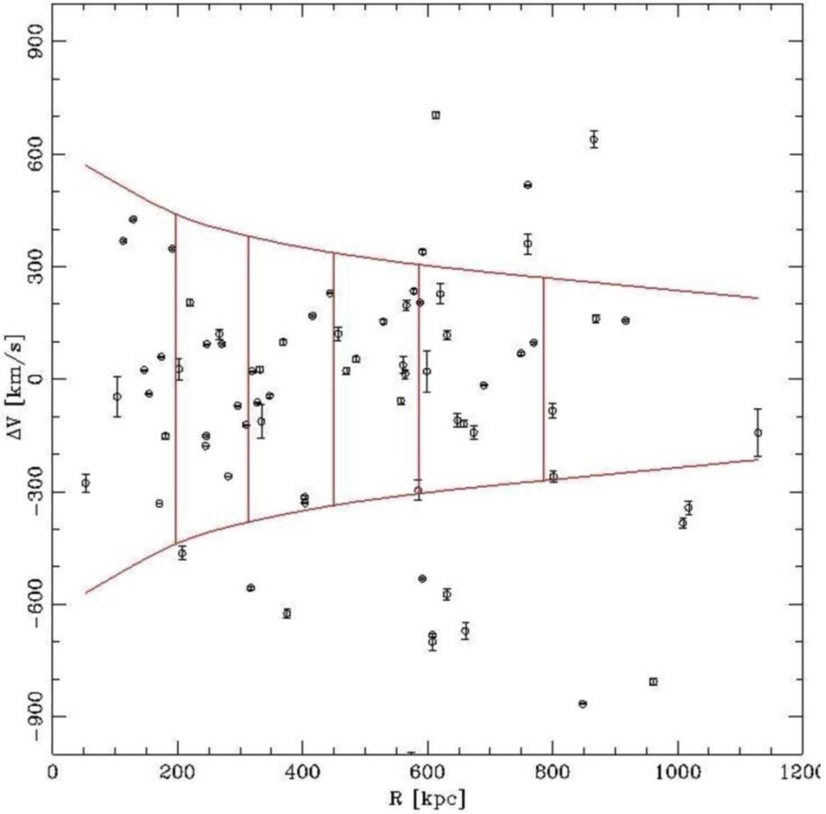


We are studying 8 isolated spiral galaxies at z = 0.03 - 0.09

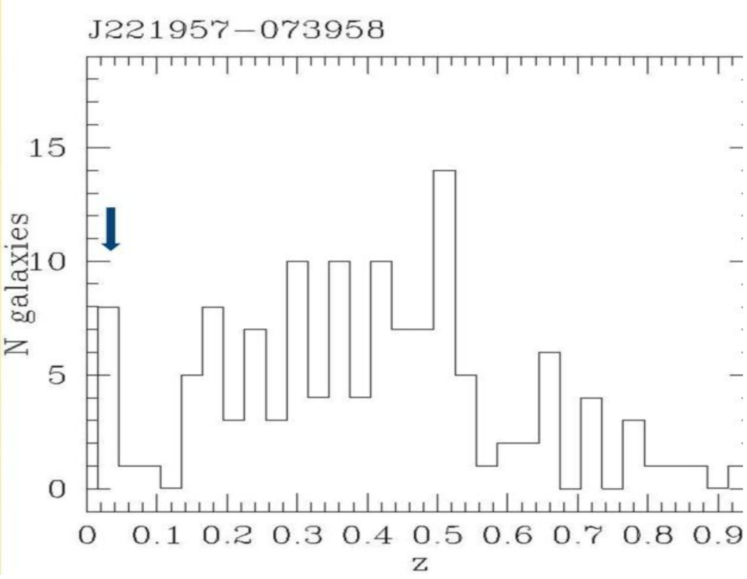
+

VIMOS **EMMI**

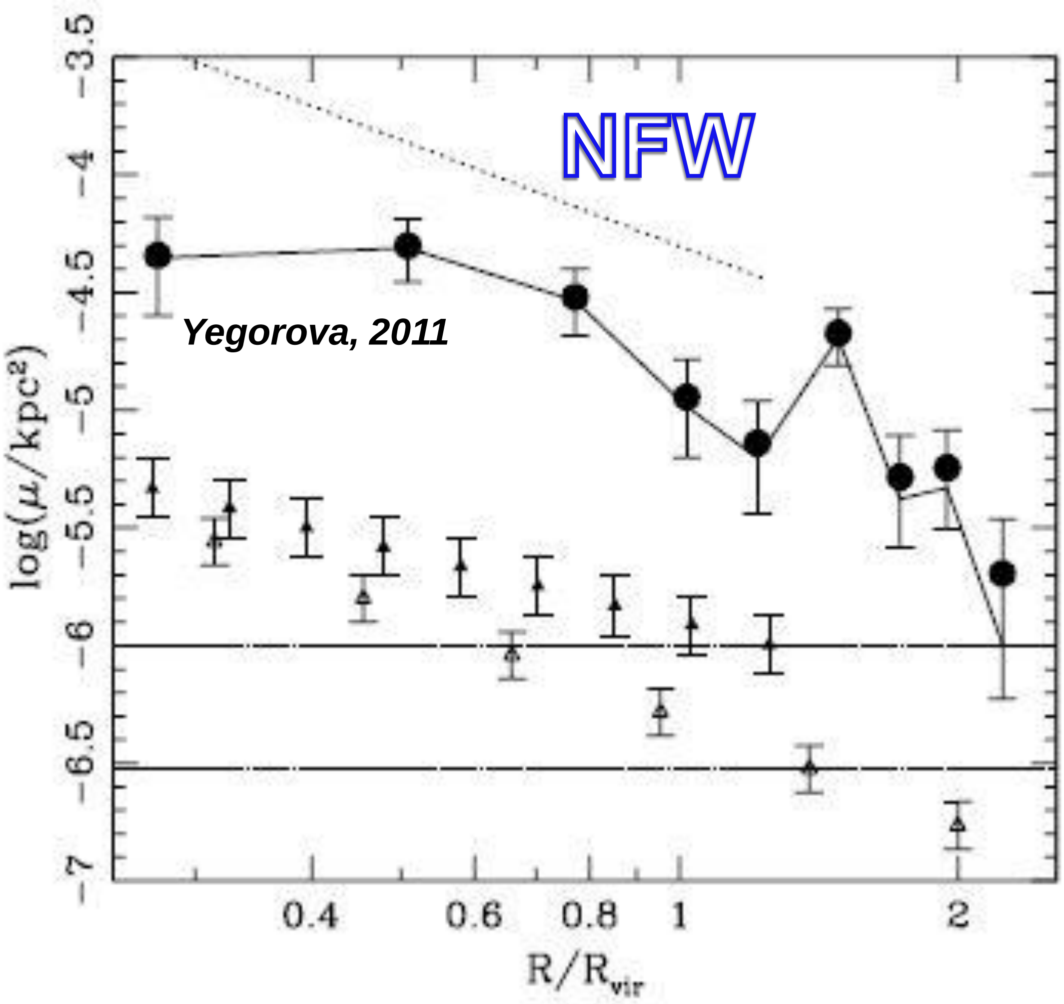
Satellites + Rotation curve



M_*> 5 10^9 M_s



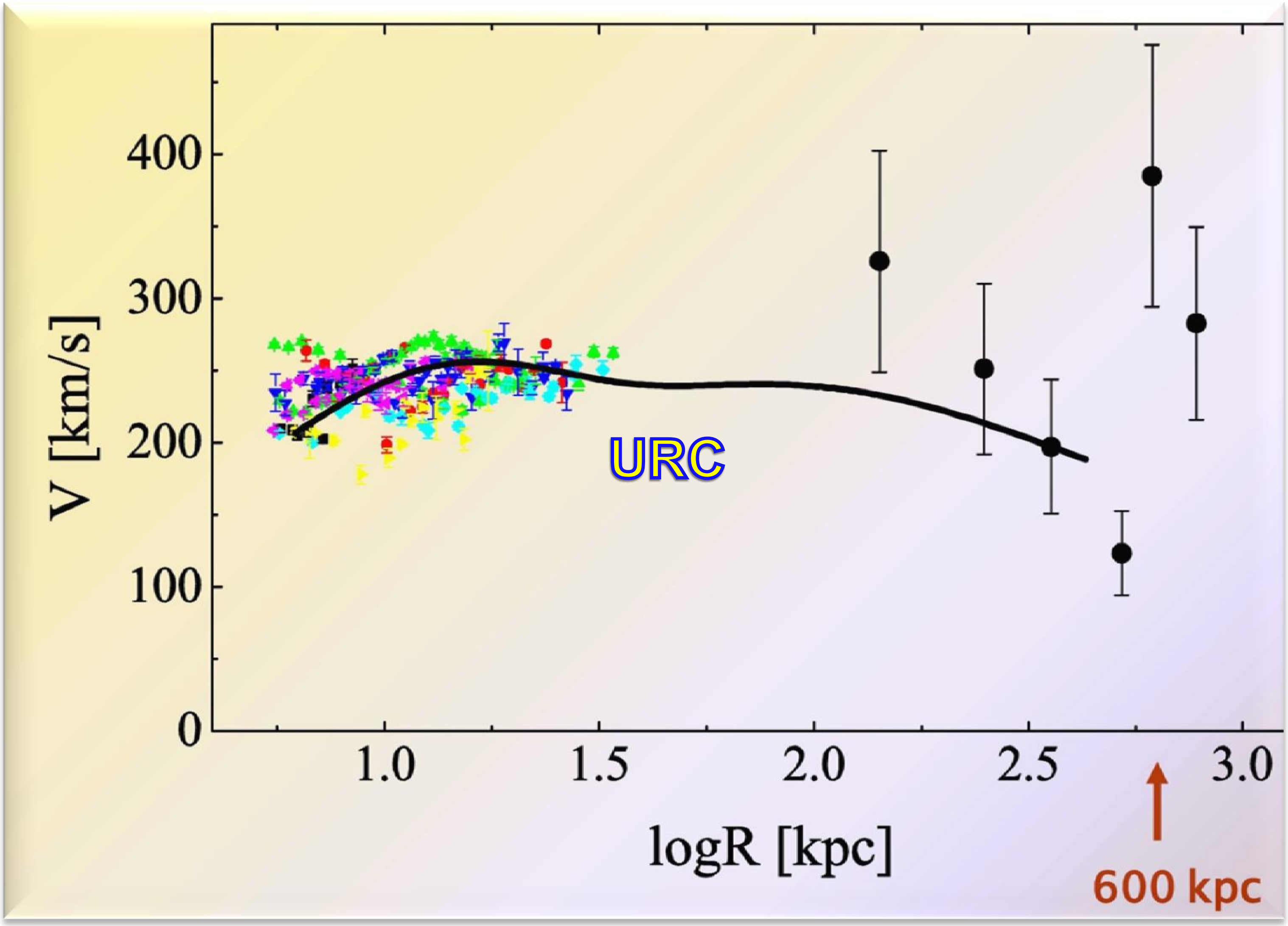
Surface density of satellites around 8 primaries


NFW

Yegorova, 2011

Salucci et al 2007

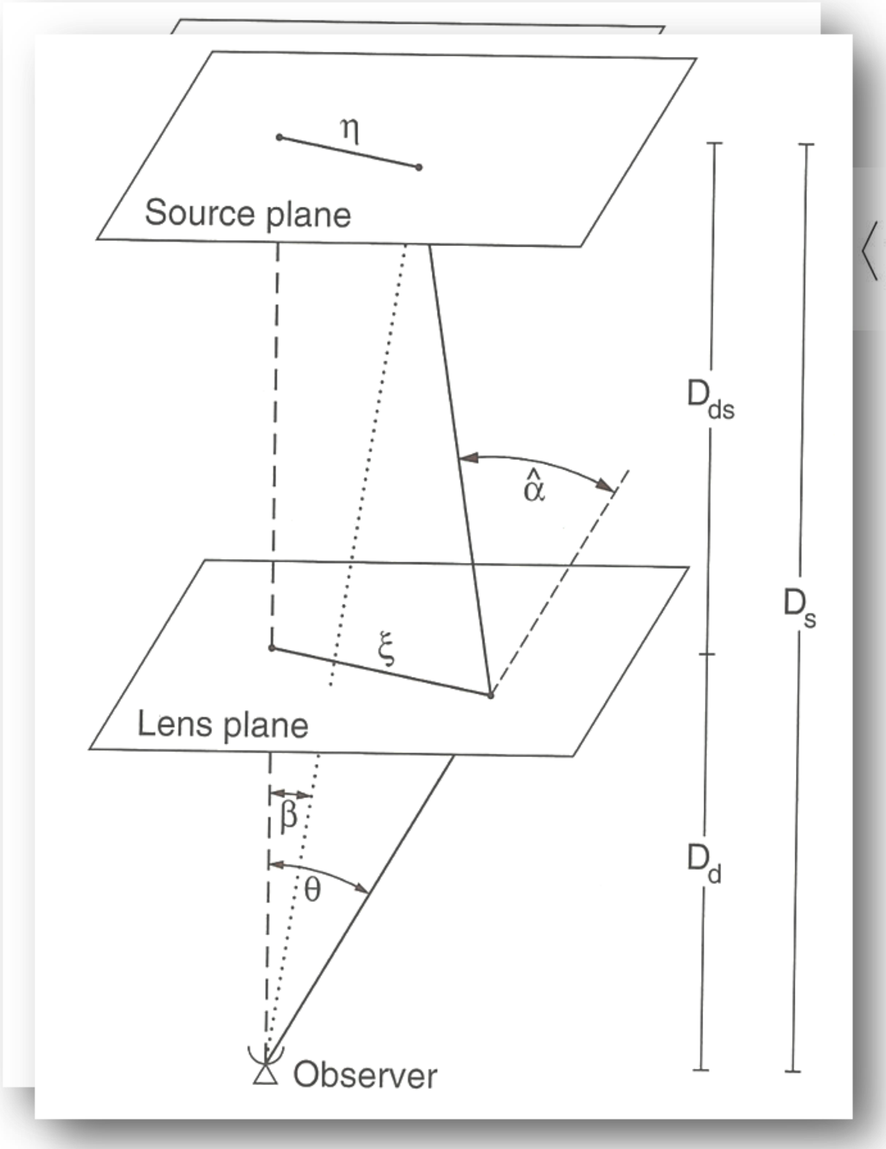
averaged circular velocity



Mass profiles from weak lensing

A ray into the darkness…

Lensing equation for the tangential shear



$$\langle \gamma_t \rangle \equiv \frac{\overline{\Sigma}(R) - \Sigma(R)}{\Sigma_c(R)}$$

$$\bar{\Sigma} = \frac{M(R)}{4\pi R^2}$$

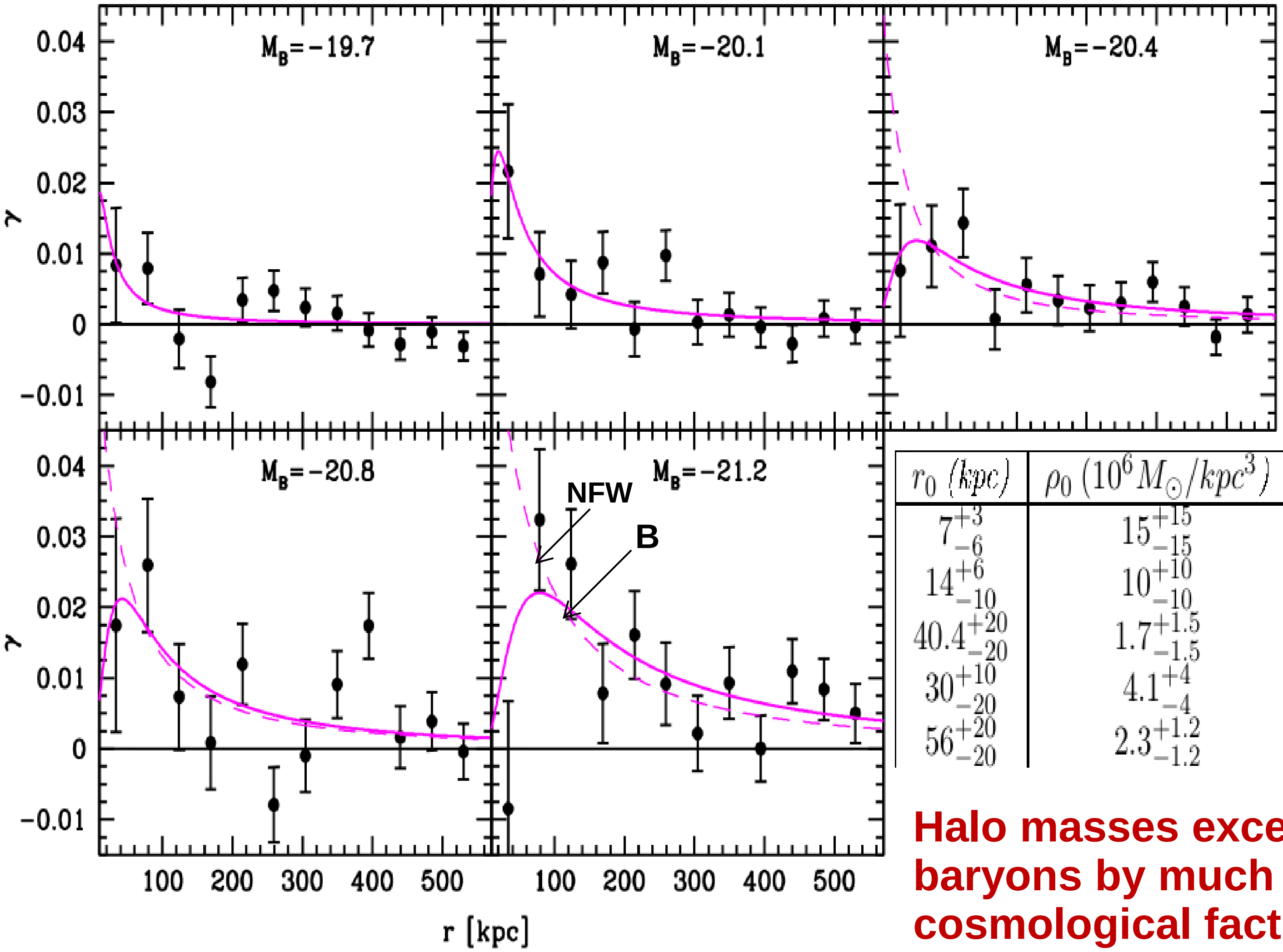
$$R = \theta D_{ol}$$

$$\boxed{\Sigma_c = \frac{c^2}{4\pi G}\frac{D_{os}}{D_{ol}D_{ls}}}$$

MODELLING WEAK LENSING SIGNALS

Lenses: 170000 isolated galaxies, sources: 3 10^7 SDSS galaxies

Donato et al 2009



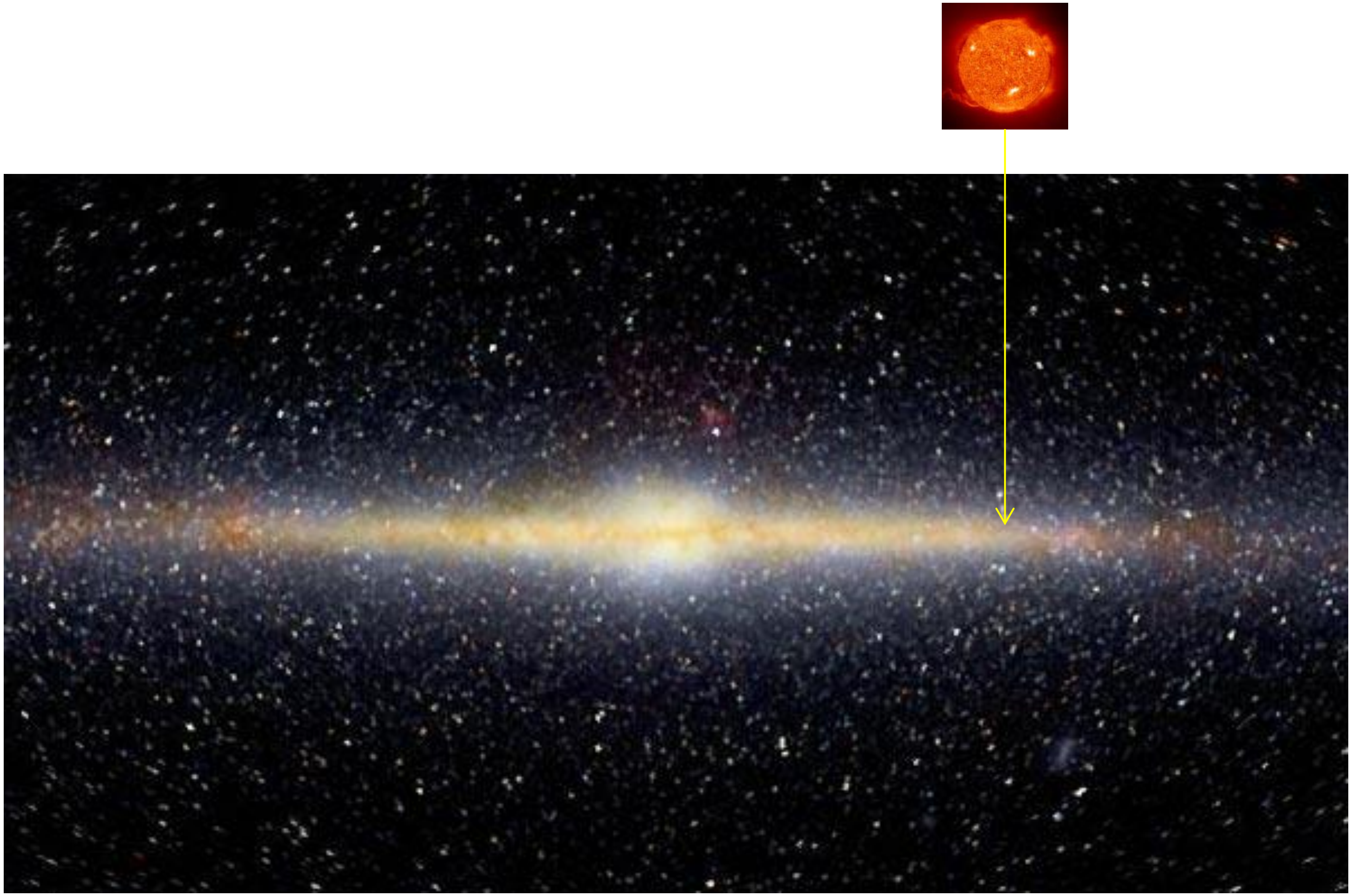
r_0 (kpc)	ρ_0 ($10^6 M_\odot/kpc^3$)
7^{+3}_{-6}	15^{+15}_{-15}
14^{+6}_{-10}	10^{+10}_{-10}
40.4^{+20}_{-20}	$1.7^{+1.5}_{-1.5}$
30^{+10}_{-20}	4.1^{+4}_{-4}
56^{+20}_{-20}	$2.3^{+1.2}_{-1.2}$

Halo masses exceed the masses in baryons by much more than the cosmological factor of 7.

Halo and baryonic masses correlate

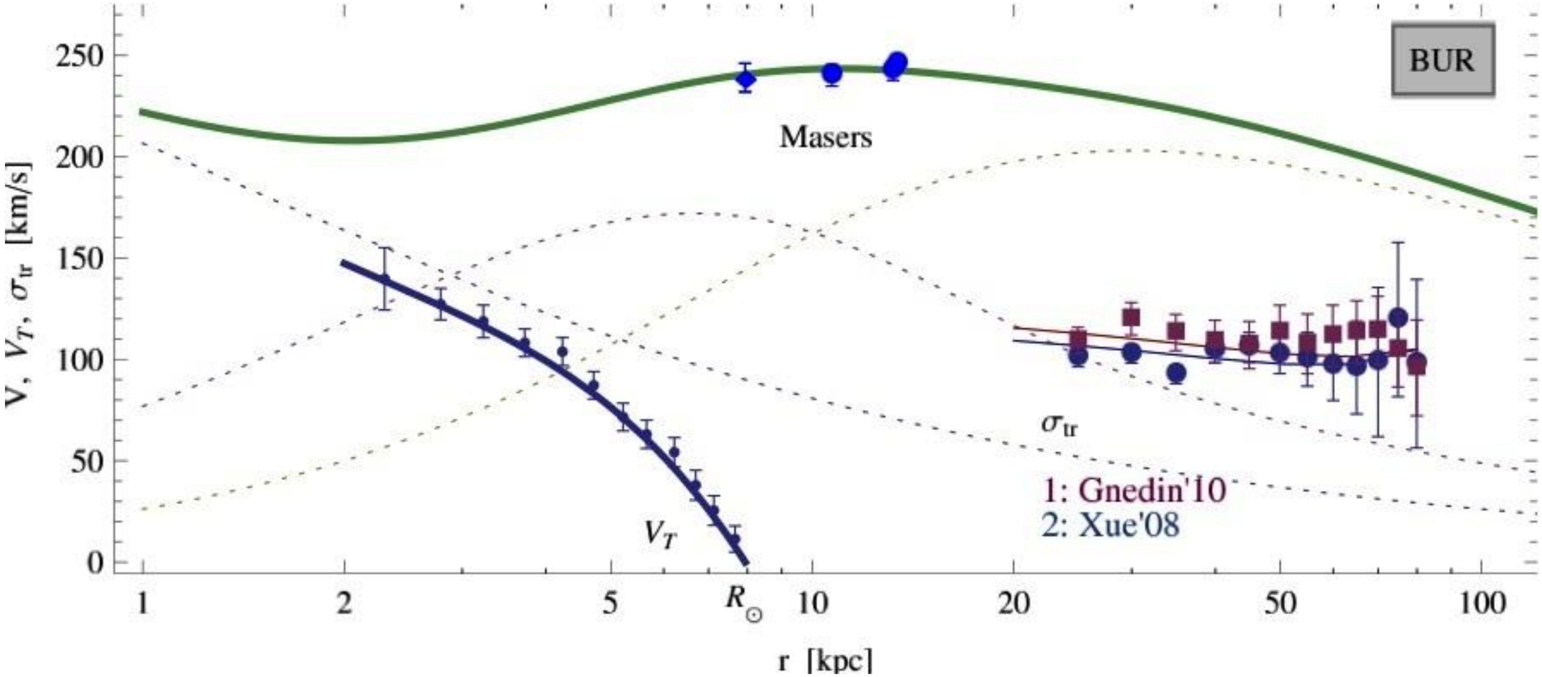
AGREEMENT WITH THE URC

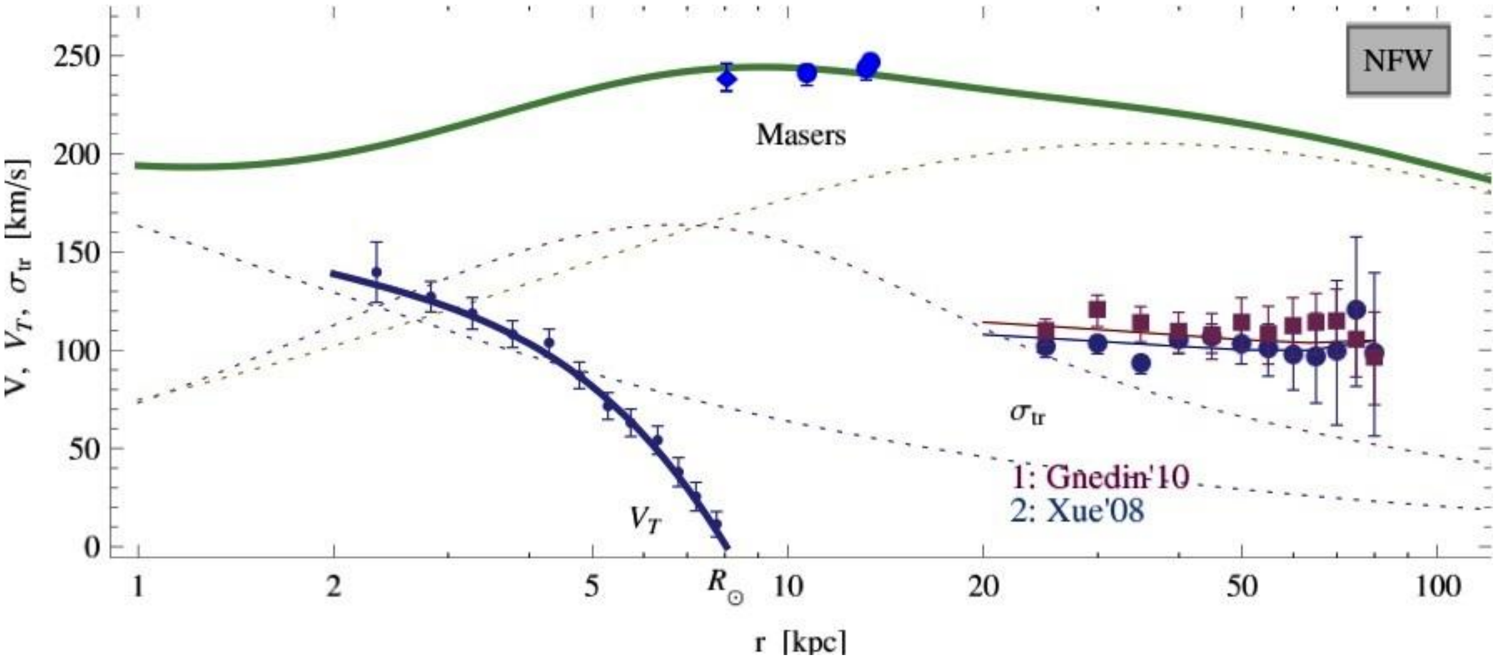
INNER : HINTS FOR CUSPS
OUTER: NFW/BURKERT PROFILE

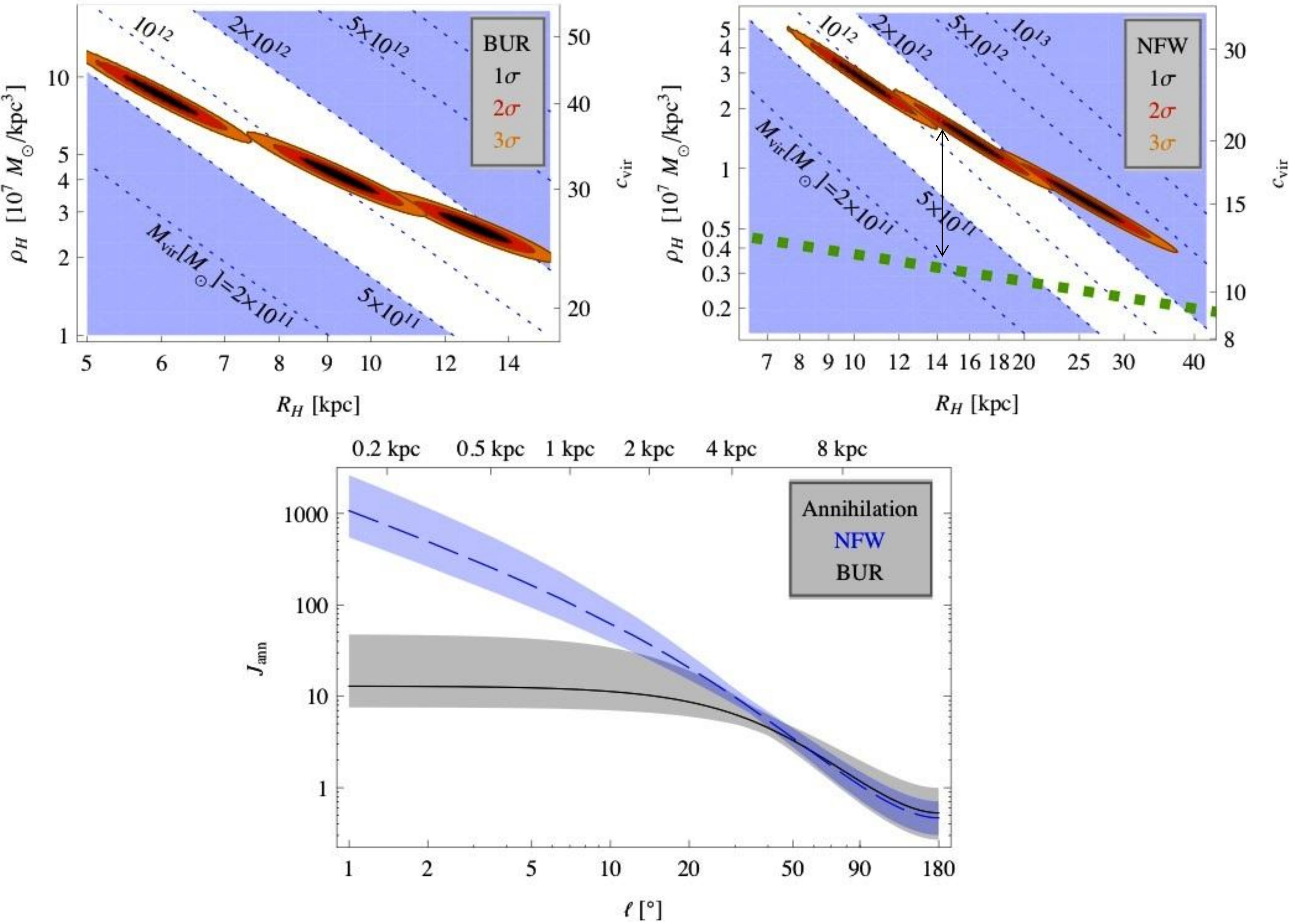


THE GALAXY

The perfect hideout for dark stuff

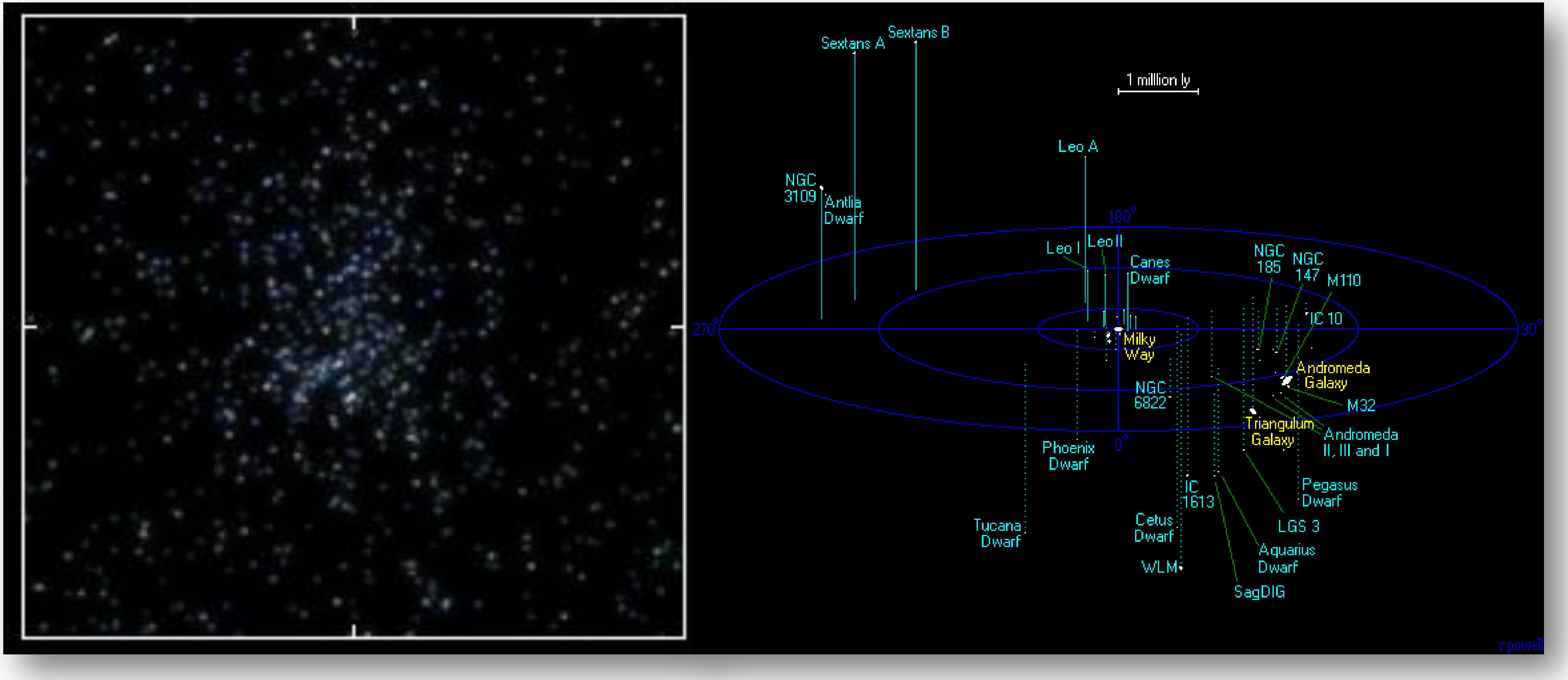

BUR
Masers
$\sigma_{\rm tr}$
1: Gnedin'10
2: Xue'08
V_T
V, V_T, $\sigma_{\rm tr}$ [km/s]
0
50
100
150
200
250
1
2
5
$R_\odot$
10
20
50
100
r [kpc]


NFW
Masers
$\sigma_{\rm tr}$
1: Gnedin'10
2: Xue'08
V_T
V, V_T, $\sigma_{\rm tr}$ [km/s]
0
50
100
150
200
250
1
2
5
$R_\odot$
10
20
50
100
r [kpc]


BUR
1σ
2σ
3σ
10^{12}
2×10^{12}
5×10^{12}
$M_{\rm vir}[M_\odot]=2\times10^{11}$
5×10^{11}
ρ_H [$10^7\,M_\odot$/kpc^3]
$c_{\rm vir}$
R_H [kpc]
NFW
1σ
2σ
3σ
10^{13}
ℓ [°]
$J_{\rm ann}$
0.2 kpc
0.5 kpc
1 kpc
2 kpc
4 kpc
8 kpc
Annihilation
NFW
BUR

dSphs

the dark side strikes back



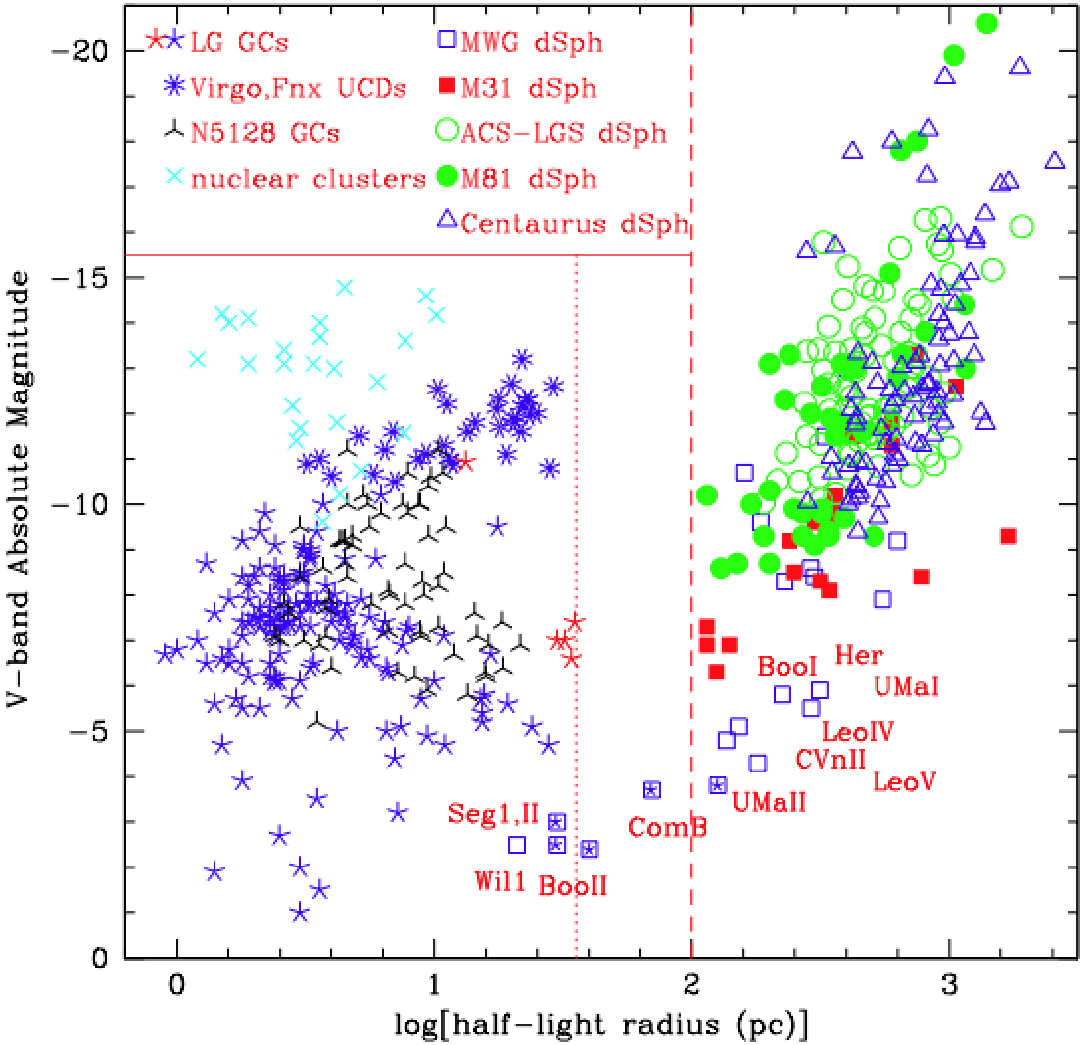
Dwarf spheroidals: basic properties

The smallest objects in the Universe, benchmark for theory

$$L = 2\times10^3 L_\odot - 2\times10^7 L_\odot \quad \sigma_0 \sim 7-12\,\mathrm{km\,s^{-1}} \quad r_0 \approx 130-500\,\mathrm{pc}$$

dSph show large M_{grav}/L

Luminosities and sizes of Globular Clusters and dSph are different



Gilmore et al 2009

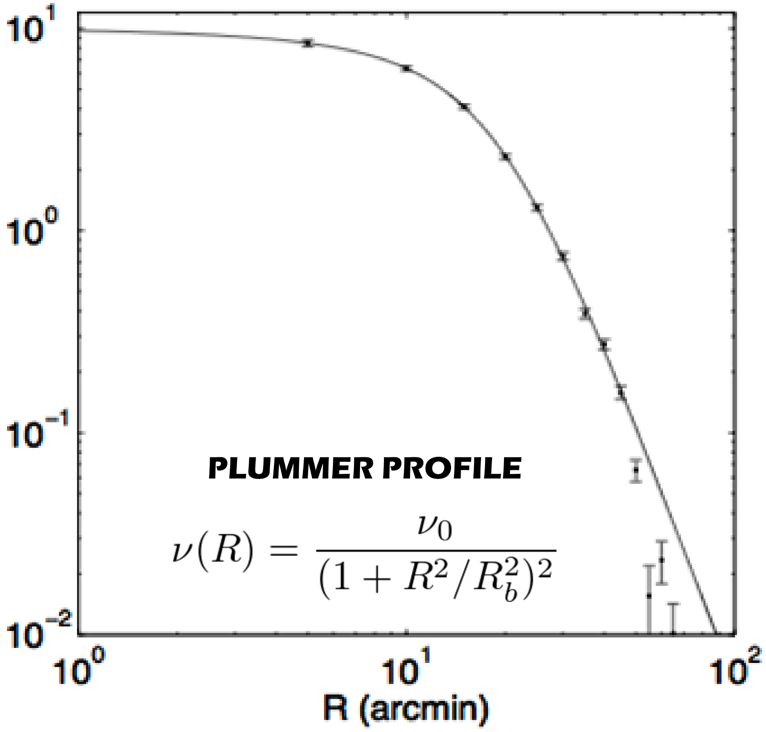
Mass profiles of dSphs

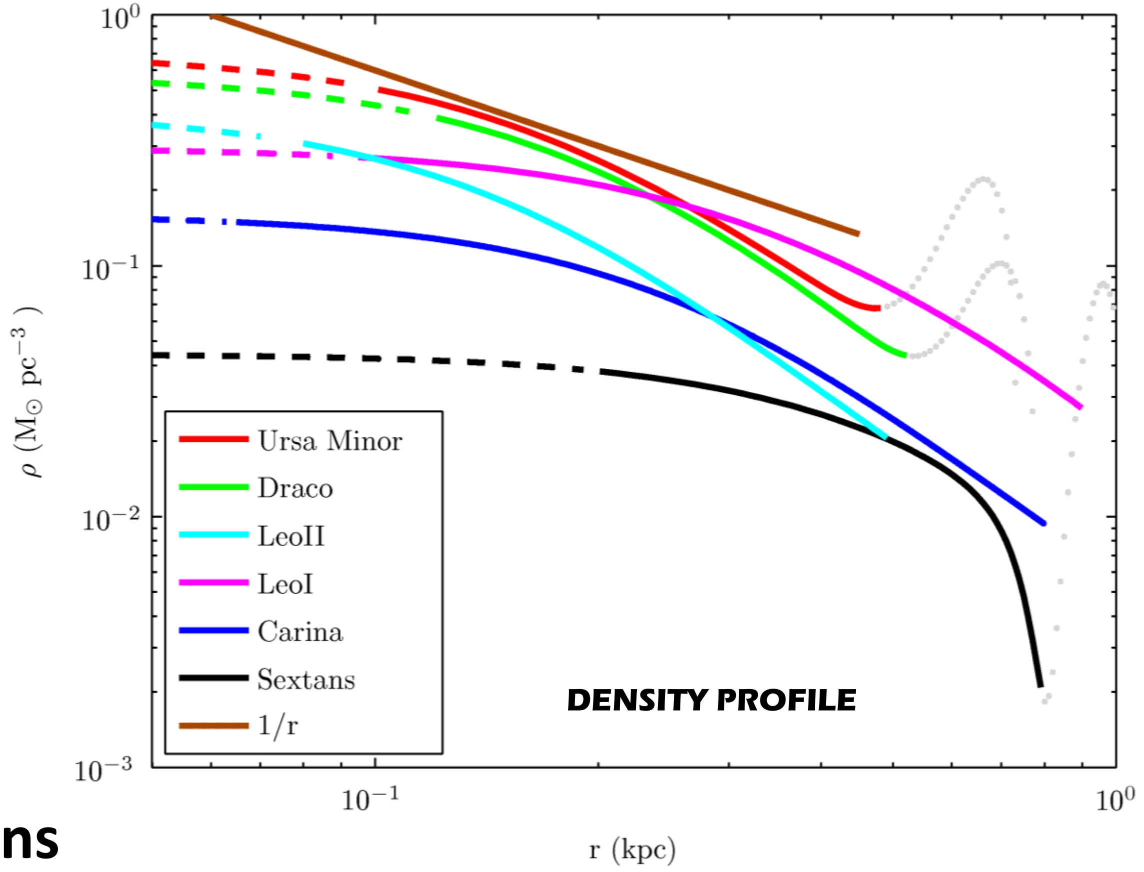
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\,\frac{\beta\sigma_r^2}{r}\right)$$

Jeans' models provide the most objective sample comparison

Jeans equation relates kinematics, light and underlying mass distribution

Make assumptions on the velocity anisotropy and then fit the dispersion profile

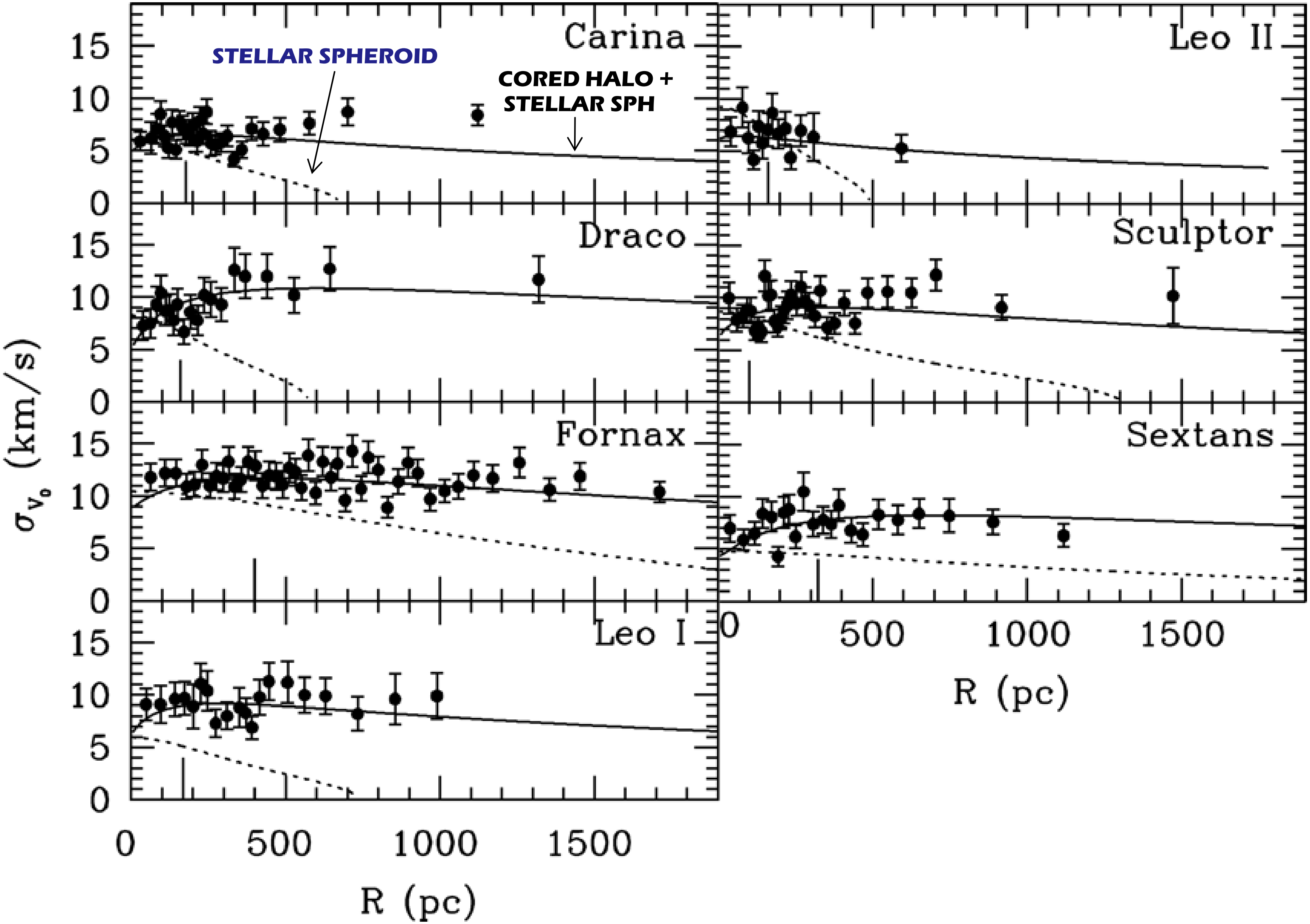




Results point to cored distributions

Gilmore et al 2007

Dispersion velocity profiles

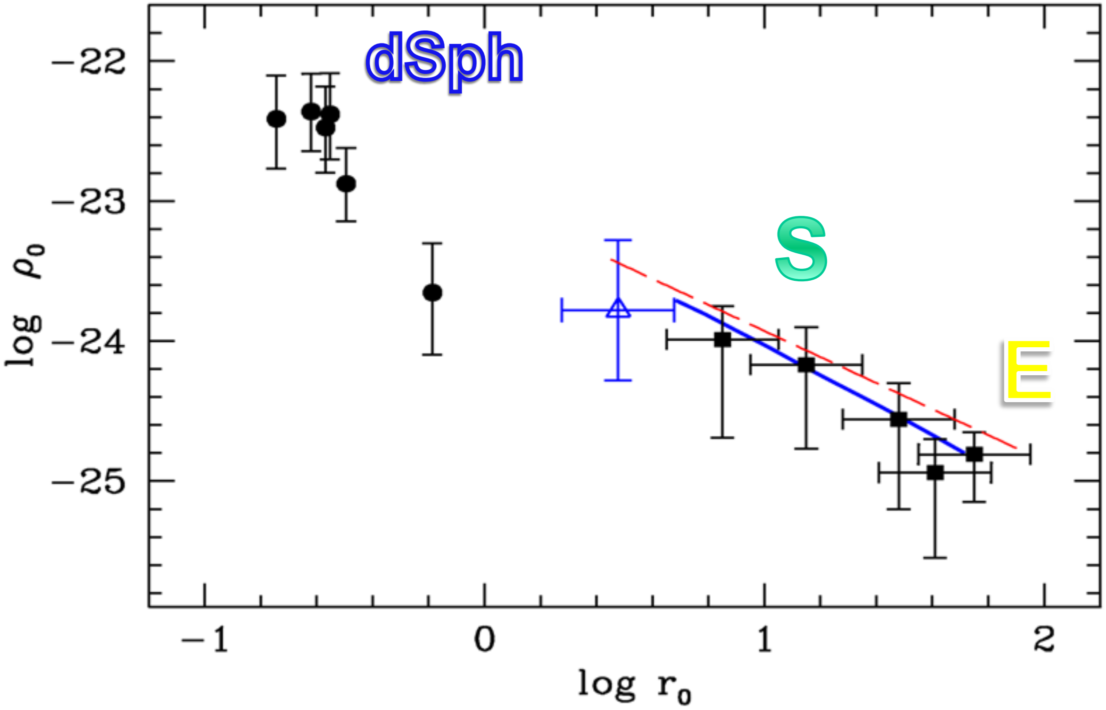


dSph dispersion profiles generally remain flat to large radii

dSphs cored halo model

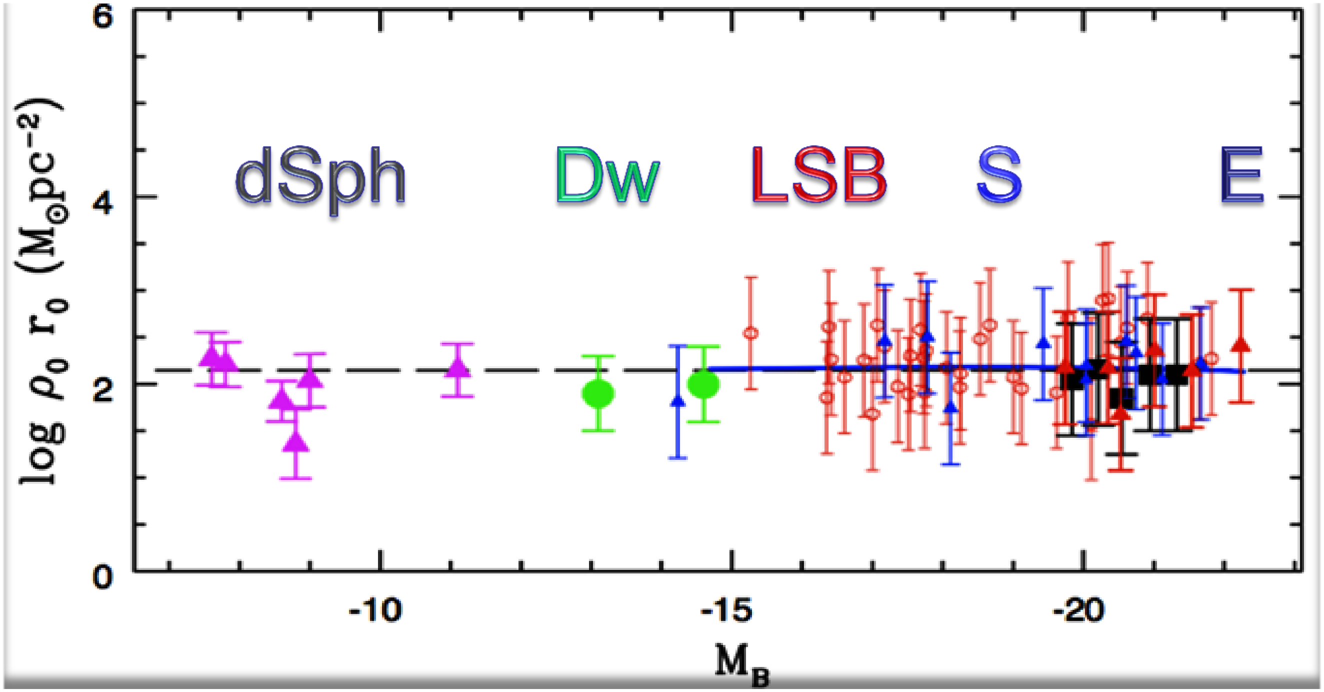
halo central densities correlate with core radius in the same way as Spirals and Ellipticals

$$\rho_0 = 10^{-23} \left(\frac{r_0}{1kpc} \right)^{-1} g/cm^3$$



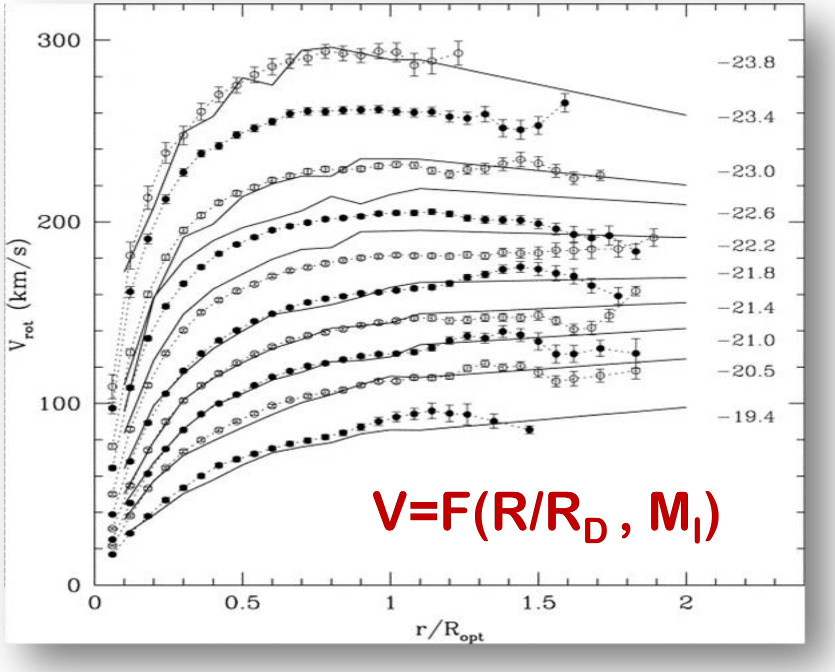
Salucci et et al 2012

GALAXY HALOS: AN UNIFIED VISION

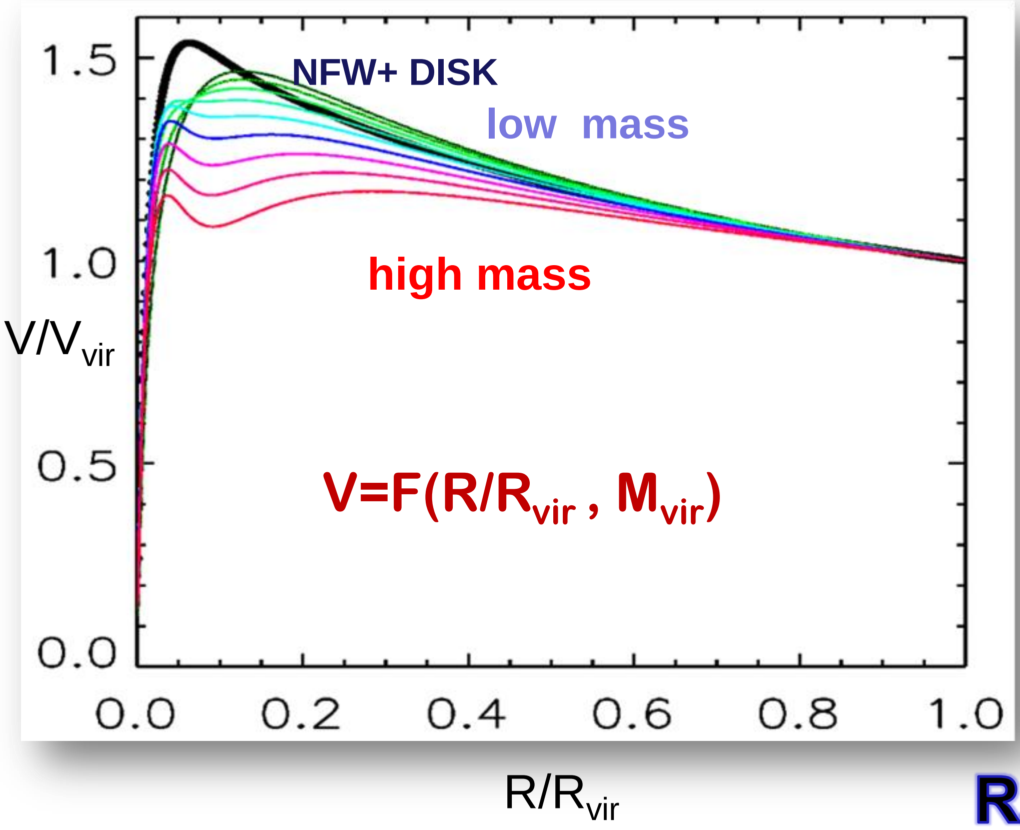


Universal Mass Distribution

URC

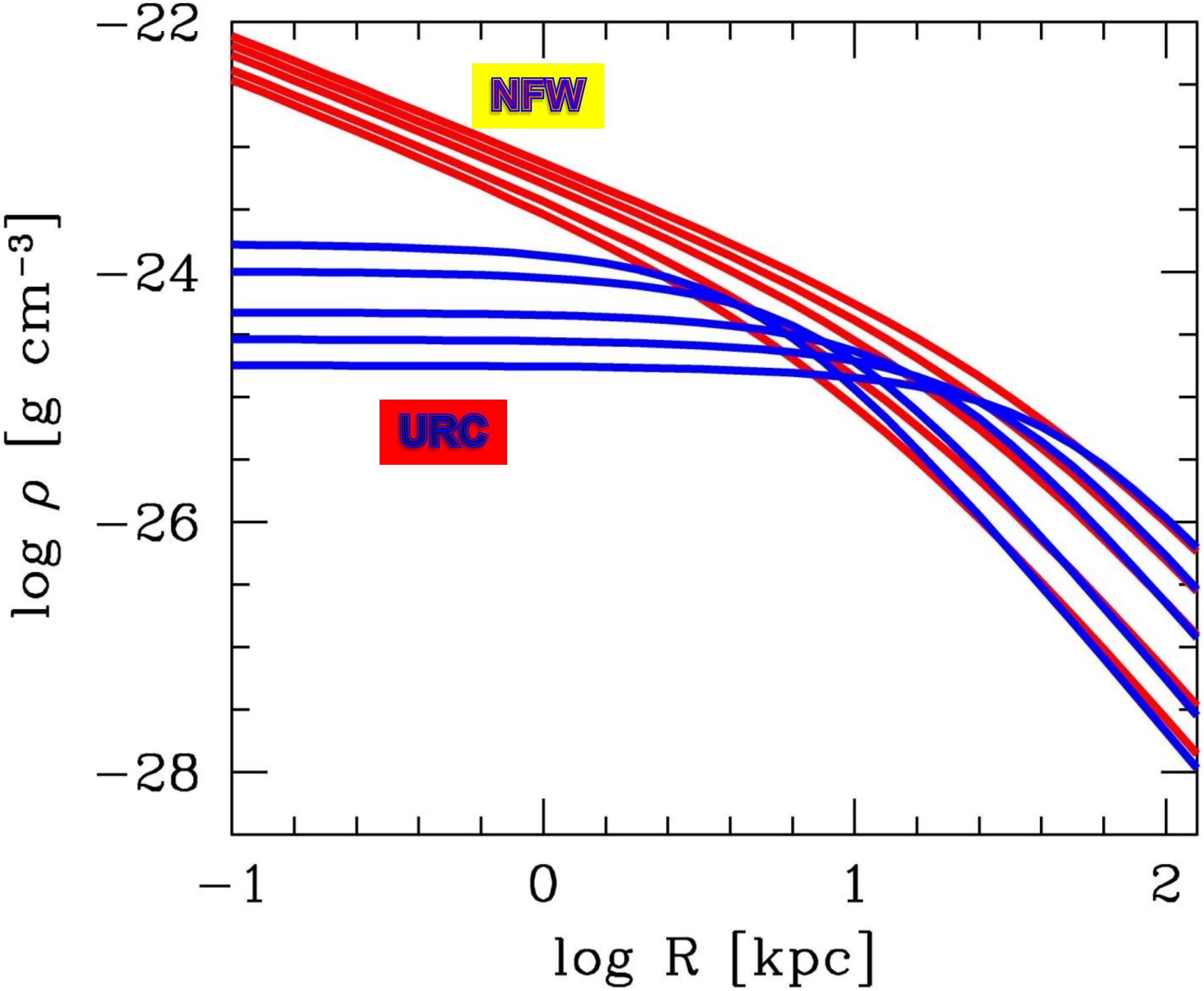


URC out to R_{vir} and ΛCDM model



R_{vir}

Universal Density Profile



De Vega & Sanchez 2013: point forward

The de Broglie wavelength of DM particles in a galaxy can be estimated as

$$\lambda_{dB} = \frac{\hbar}{m\,\sigma} ,$$

while the average interparticle distance d can be estimated as

$$d = \left(\frac{m}{\rho_h}\right)^{\frac{1}{3}} ,$$

where ρ_h is the average density in the galaxy core. By using $\rho_h = \sigma^3 \; Q_h$
can express the ratio

$$\mathcal{R} \equiv \frac{\lambda_{dB}}{d}$$

as,

$$\mathcal{R} = \hbar \left(\frac{Q_h}{m^4}\right)^{\frac{1}{3}} .$$

Using now the observed values of Q_h

$$2 \times 10^{-3} < \mathcal{R} \left(\frac{m}{\mathrm{keV}}\right)^{\frac{4}{3}} < 1.4$$

Notice that here as well as in the bound eq.(13) $\hbar^3 \; Q/m^4$ measures how quantum or classical is the system (the galaxy).

We conclude **solely from observations** that compact dwarf galaxies are natural macroscopic quantum objects for WDM.

Dwarf Galaxies supported by WDM fermionic quantum pressure

For an order–of–magnitude estimate, let us consider a halo of mass M and radius R of fermionic matter. It can be fermionic DM or baryons. Each fermion can be considered inside a cell of size $\Delta x \sim 1/n^{\frac{1}{3}}$ and therefore has a momentum

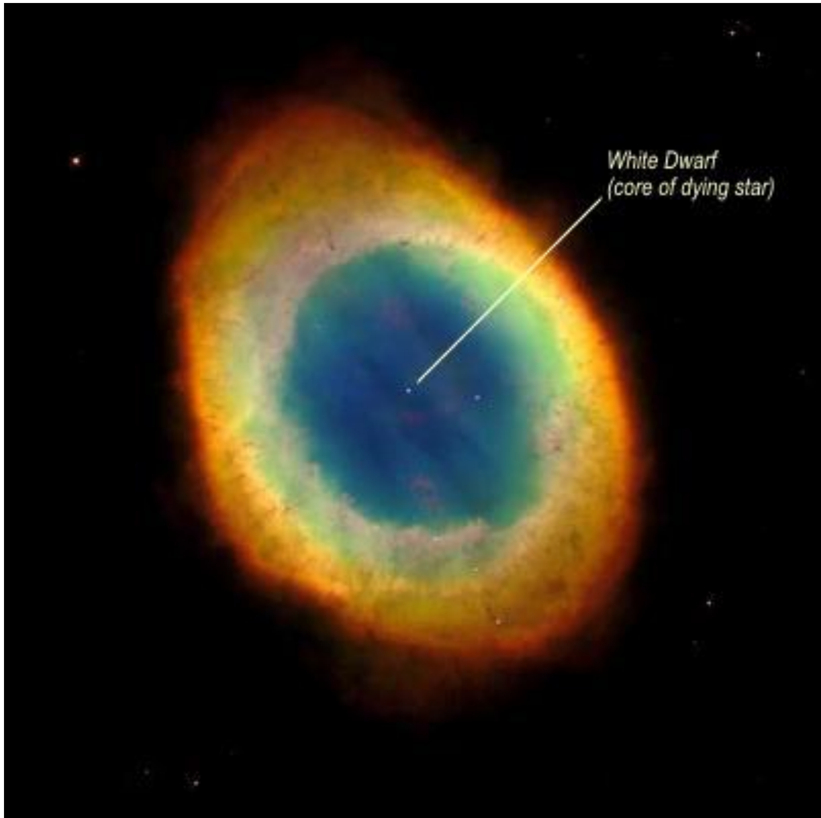
$$p \sim \frac{\hbar}{\Delta x} \sim \hbar\, n^{\frac{1}{3}} \ .$$

The associated quantum pressure P_q (flux of the momentum) has the value

$$P_q = n\, \sigma\, p \sim \hbar\, \sigma\, n^{\frac{4}{3}} = \frac{\hbar^2}{m}\, n^{\frac{5}{3}} \ .$$

where σ is the mean velocity

$$\sigma = \frac{p}{m} = \frac{\hbar}{m}\, n^{\frac{1}{3}} \ .$$



The system will be in dynamical equilibrium if this quantum pressure is balanced by the gravita-ional pressure

$$P_G = \text{gravitational force/area} = \frac{G\,M^2}{R^2} \times \frac{1}{4\,\pi\,R^2}$$

We estimate the number density as

$$n = \frac{M}{\frac{4}{3}\,\pi\,R^3\,m}\ ,$$

and we use that $p = m\,\sigma$ to obtain

$$P_q = \frac{\hbar^2}{m\,R^5}\left(\frac{3\,M}{4\,\pi\,m}\right)^{\frac{5}{3}}\ .$$

Equating $P_q = P_G$ yields the following relations

$$R = \frac{3^{\frac{5}{3}}}{(4\,\pi)^{\frac{2}{3}}}\,\frac{\hbar^2}{G\,m^{\frac{8}{3}}\,M^{\frac{1}{3}}} = 10.6\ldots\text{pc}\left(\frac{10^6\,M_\odot}{M}\right)^{\frac{1}{3}}\left(\frac{\text{keV}}{m}\right)^{\frac{8}{3}}$$

$$\sigma = \left(\frac{4\,\pi}{81}\right)^{\frac{1}{3}}\,\frac{G}{\hbar}\,m^{\frac{4}{3}}\,M^{\frac{2}{3}} = 22.9\ldots\frac{\text{km}}{\text{s}}\left(\frac{m}{\text{keV}}\right)^{\frac{4}{3}}\left(\frac{M}{10^6\,M_\odot}\right)^{\frac{2}{3}}\ .$$

Notice that the values of M, R and σ are consistent with dwarf galaxies. Namely, for M of the order $10^6\ M_\odot$ (typical mass value for dwarf spheroidal galaxies), R and σ have the correct order of magnitude for dwarf spheroidal galaxies for a WDM particles mass in the keV scale (see Table

CONCLUSIONS

The distribution of DM in halos around galaxies shows a striking and complex phenomenology leading to a non trivial cosmological setting.

The nature of dark matter is decisive to understand intricate galaxy formation process